UNIVERSITY OF TAMPERE
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RAPID PROTOTYPING AS A POTENTIALLY DISRUPTIVE TECHNOLOGY FOR AN R&D FOCUSED COMPANY – CASE OUTOTEC

Business Management
Master's Thesis
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SUMMARY

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This research report examined rapid prototyping as a potentially disruptive technology for an R&D focused company. The focus was on how rapid prototyping technology affects the design process and prototyping as they are critical for the success of R&D focused companies.

To describe what makes certain technologies disruptive and how they evolve, a theoretical framework for the study reviewed related literature of theories on technology driven business disruptions.

As a secondary data, previous literature and research reports were used to describe the design process, prototyping and rapid prototyping. The literature review and findings from the secondary data were complemented with the empirical findings from the single case study which examined how rapid prototyping affects design process and prototyping. The primary data of the case was gathered mainly from the interviews. In this research report, the findings from the primary data were cross checked with findings from the secondary data and theory on disruptive technologies.

The research report findings indicate that rapid prototyping is a potentially disruptive technology for R&D focused companies. Rapid prototyping seems to evolve as either low-end disruption or new-market disruptions. The context where rapid prototyping is used seems to define whether rapid prototyping can be seen as a disruptive technology or not. R&D focused product leadership companies need to be aware of the progress of rapid prototyping closely and consider adopting it, as this research report showed that rapid prototyping can bring many benefits for the design process and prototyping. It also has potential to drive many other market disruptions.

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Tutkimuksen aiheena on pikamallinnus potentiaalisesti murroksellisena teknologiana tuotekehityslähtöisille yrityksille. Tutkimus keskittyy siihen, miten pikamallinnusteknologia vaikuttaa tuotekehitysprosessiin ja mallintamiseen, koska nämä ovat kriittisiä prosesseja tuotekehityslähtöisille yrityksille.

Kirjallisuuskatsauksessa on käsitelty murroksellisiin teknologioihin ja niiden omaksumiseen liittyvää kirjallisuutta. Kirjallisuuskatsaus kuvaa sitä, mikä tekee tietyistä teknologioista murroksellisia ja miten murrokselliset teknologiat kehittyvät.

Aikaisempaa kirjallisuutta ja tutkimuksia on käytetty toissijaisena aineistona kuvaamaan tuotekehitysprosessia, mallintamista, sekä pikamallintamista. Kirjallisuuskatsausta sekä löydöksiä toissijaisesta ainestosta on täydennetty empiirisillä tuloksilla tapaustutkimuksesta. Tapaustutkimus keskittyy siihen, miten pikamallintaminen vaikuttaa tuotekehitysprosessiin sekä mallintamiseen. Ensisijainen aineisto tapaustutkimukseen on kerätty pääasiassa haastatteluiden avulla. Tässä tutkimuksessa ensisijaisen aineiston tuloksia on verrattu toissijaisen aineiston löydöksiin sekä kirjallisuuskatsaukseen.

Tämän tutkimusraportin mukaan pikamallintaminen on potentiaalisesti murroksellinen teknologia tuotekehityslähtöisille yrityksille. Pikamallintaminen näyttää kehittyvän sekä matalantason murroksena että uusien markkinoiden murroksina. Konteksti, jossa pikamallinnusta käytetään, näyttää määrittävän onko pikamallintaminen murroksellinen teknologia vai ei. Tuotekehityslähtöisten yritysten tulee tämän tutkimuksen perusteella olla tietoisia pikamallintamisen kehittymisestä ja harkita sen käyttöönottoa, koska pikamallintaminen voi tuoda monia hyötyjä tuotekehitysprosessiin ja mallintamiseen. Se voi potentiaalisesti aihettaa myös monia muita markkinamurroksia.

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LIST OF ABBREVIATIONS

3D = Three dimensional

3DP = 3D Printing

CAD = Computer-aided Design

CAE = Computer-aided Engineering

CAM = Computer-aided Manufacturing

CFD = Computerized Fluid Dynamics

DFA = Design for Assembly

DFM = Design for Manufacture

FDM = Fused Deposit Modeling

FGM = Functionally Graded Material

RP = Rapid Prototyping

R&D = Research and Development

SL = Stereolithography

SLA = Stereolithography Apparatus

SLS = Selective Laser Sintering

1. Introduction

1.1 Background

> *"Last year, we created our first manufacturing innovation institute in Youngstown, Ohio. A once-shuttered warehouse is now a state-of-the art lab where new workers are mastering the 3D printing that has the potential to revolutionize the way we make almost everything* --- *I ask this Congress to help create a network of fifteen of these hubs and guarantee that the next revolution in manufacturing is Made in America."*

- Barack Obama, president of the United States, in his annual State of the Union address on February 12, 2013 (Source: The Guardian website <http://www.guardian.co.uk/world/2013/feb/13/state-of-the-union-full-text>)

3D Printing is currently constantly in the headlines. In the popular press 3D printing is used to describe all kinds of additive technologies that create objects layer-by-layer. The headlines of those kinds of news are looking forward to the future and expecting that 3D printing is changing many fundamental things. Examples of these expectations presented in the press are that 3D printing will change the way manufacturing is done (e.g. The Economist 2012c, Remes 2012), consumers will commonly have 3D printers as their home accessory (Segall 2011), buildings will be 3D printed (BBC News 2013) and even lunar bases might be built using 3D printing (European Space Agency 2013). In general, there seems to be a great belief that 3D printing will change the future radically.

Gartner, the information technology research and advisory company (Gartner website: http://www.gartner.com/technology/about.jsp), researches the development of technologies through its own model called the Hype Cycle. The Hype Cycle model follows the pattern of hope and disappointment of new technologies as they seem to go through the same kind of phases of expectations. (Fenn & Raskino 2008) According to Gartner, 3D Printing is currently at the peak of inflated expectations in the Hype Cycle (Figure 1).

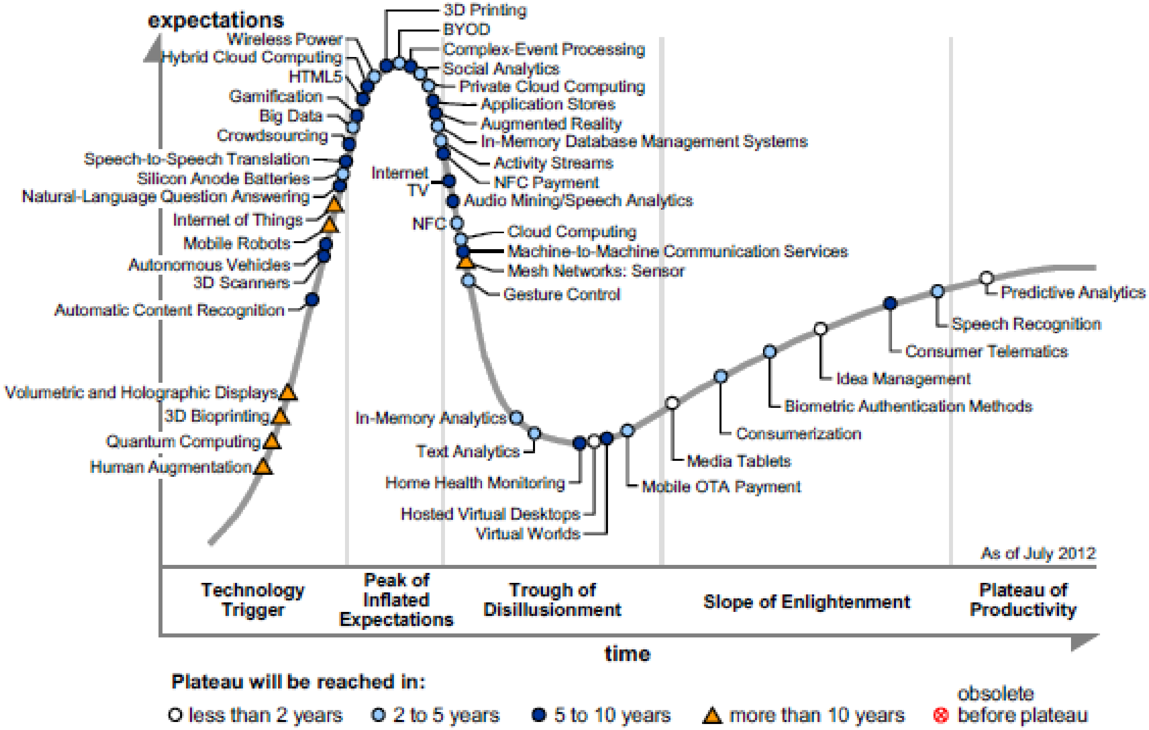

Figure 1 Hype Cycle for Emerging Technologies (Gartner 2012)

In this phase, the companies that want to be ahead of their competitors adopting the technology will exploit it. The press captures the excitement around the innovation and other companies want to join, so they are not left behind. But as the time passes, impatience for results begins to replace the original excitement about potential value of the new technology. Problems with performance or, for example, slower-than-expected adoption start to lead to missed expectations and the technology moves to the trough of disillusionment. (Fenn & Raskino 2008)

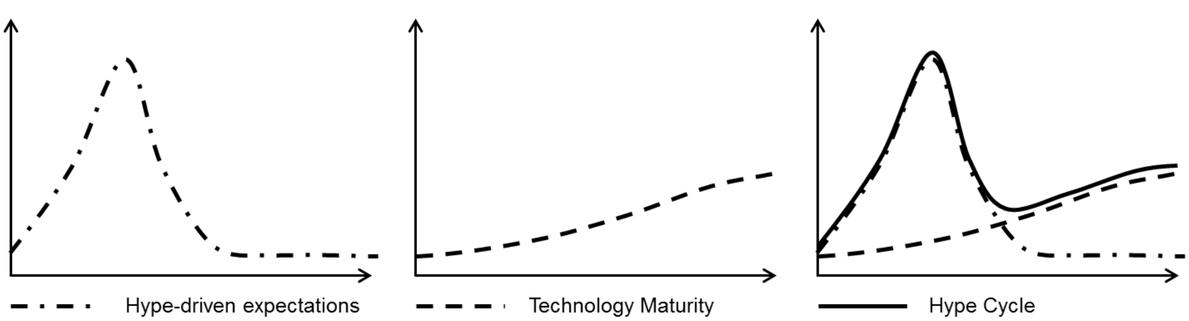

Figure 2 Components of the Hype Cycle (Fenn & Raskino 2008, 26)

The hype-driven expectations for 3D printing are currently at their peak, but usually at the same time the technology maturity is not yet sufficient to fulfill those expectations (Figure 2). Thus the trough of disillusionment is probably also the next phase for 3D printing as the technology does not mature at the phase expected. Only at the plateau of productivity, has the technology reached the mainstream stage of maturity, where the technology is considered proven and it has a relatively predictable value proposition and the risks of adopting it have been significantly lowered. (Fenn & Raskino 2008)

Industrial product leaders like the case company of this research report Outotec Oyj, should be following the progress of 3D printing in the Hype Cycle, as Gartner expects that the highest impact for 3D printing will be in Industrial, Consumer Products & Manufacturing. Gartner expects that it will take approximately thirteen years for 3D printing to achieve the plateau of productivity where the mainstream markets are reached and the use of 3D printers has become common. Current non-adoption risk to the high-impact industry, where Outotec Oyj also operates, is medium. (Gartner 2011) (Figure 3)

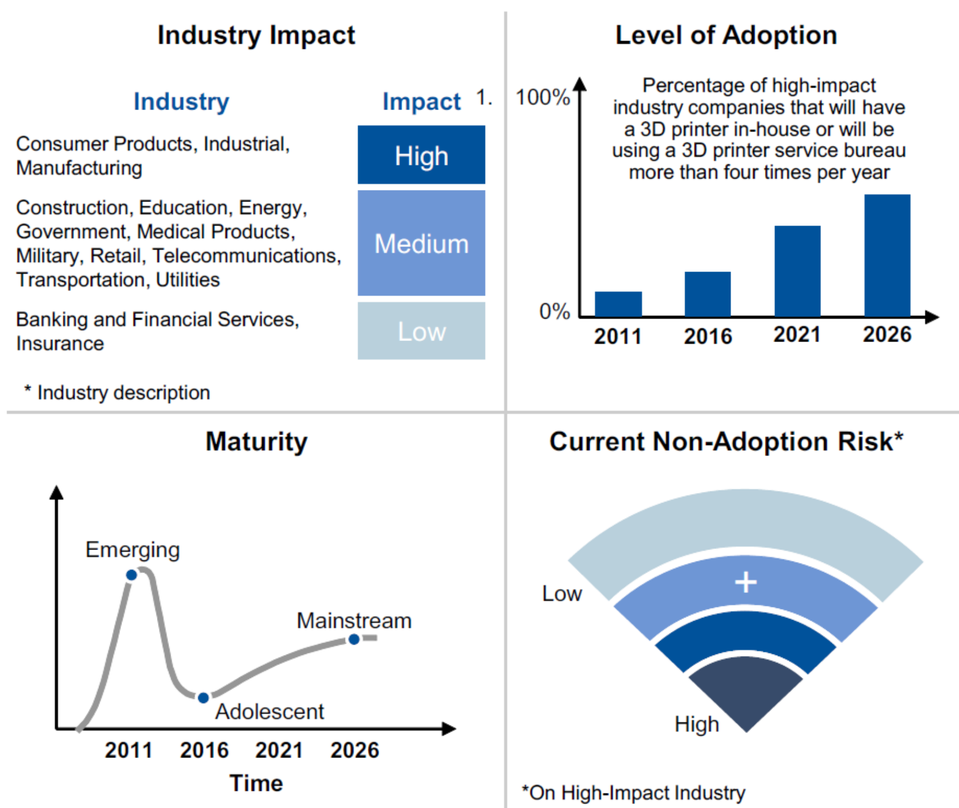

Figure 3 3D Printing Innovation Impact (Gartner 2011)

Case company Outotec Oyj (later Outotec) is a Finnish technology company with a strong market position and technology leadership in minerals and metals processing technologies. Outotec was formed, when Outokumpu Technology was organized as a legal consolidated group in 2006 and later in April 2007, according to the agreement made with the former parent company Outokumpu Oyj, it changed its name to Outotec. (Source: Outotec Oyj website < http://www.outotec.com/en/About-us/History/ >).

Outotec's business is based on a strong portfolio of world-class technologies and robust expertise. To stay at the forefront of the industry, Outotec continuously develops its proprietary technologies. (Source: Outotec Oyj website <http://www.outotec.com/en/About-us/Research-and-technology/>) Thus the R&D function, product development processes and prototyping are at the center of its success and strategically important. 3D printing is a technology that can have a radical impact on how these processes are done. Thus understanding, adopting and following the progress of this technology is important for companies like Outotec, which competitive advantage comes from product leadership (c.f. Treacy & Wierseman 1995).

Previous research has shown that rapid prototyping has reduced both the cost and time-scales involved in the design process and prototyping (e.g. Atzeni & Salmi 2012, Evans & Cambell 2003). But no previous research was found where the answer would have been looked for the question, whether rapid prototyping can potentially cause technology driven business disruptions.

This research report examines the disruptive potential of 3D printing. The focus is on how 3D printing affects the design process and prototyping. Instead of the term 3D printing, the term *rapid prototyping* is widely used in this research report. Rapid prototyping is defined as layer-by-layer fabrication of physical *prototypes* directly from a computer-aided design (CAD). This term is also widely used in professional articles and thus it has been selected to be used in this research report. According to this definition 3D printing is one of the rapid prototyping technologies used to produce prototypes. These terms and technologies will be described in more detail later in this research report.

1.2 Objective of this research

The main objective of this research report is to describe and analyze rapid prototyping as a potentially disruptive technology for an R&D focused company. As described earlier, Outotec is a product leader in minerals and metals processing technologies. Thus it has been selected as the case company. The focus is on how rapid prototyping affects the design process and prototyping, as they are critical for the business of R&D focused company like Outotec. The design process and prototyping of Outotec Larox CC filter part, called vacuum connection, was selected as the empirical case of this research report.

To achieve the main objective of this research, the following empirical research questions need to be addressed:

- What makes rapid prototyping a potentially disruptive technology?
- How rapid prototyping affects the case company's design process and prototyping?

1.3 Key concepts and terms

There are a number of different terms used to describe additive technologies where objects are created layer-by-layer (e.g. Chua, Leong & Lim 2010, 17-18; Gibson, Rosen & Stucker 2010, 6-8). In the popular press the most common term used is 3D printing, which describes additive manufacturing in general regardless of the context (e.g. The Economist 2012b, Segall 2011). In professional literature 3D printing is one of the additive technologies (e.g. Chua et al. 2010; Gibson et al. 2010, Hopkinson & Dickens 2006, Cooper 2001). In most recent articles, terms describing *additive manufacturing done layer-by-layer* are split according to the context where additive technologies are used. The term rapid prototyping has been used for many years, because additive technologies were first used in making prototypes. As additive technologies have advanced they are also used to manufacture end products and tools used in production. Thus the terms rapid manufacturing and rapid tooling have started to be taken into use.

Here the main terms used in this research report are defined.

Rapid Prototyping: There are multiple definitions for rapid prototyping (e.g. Cooper 2001, Gibson et al. 2010). In this research report rapid prototyping refers to layer-by-layer fabrication of physical *prototypes* directly from a computer-aided design (CAD).

Prototype: An approximation of a product (or system) or its components in some form for a defined purpose in its implementation (Chua et. al 2010, 2).

Prototyping: Process of realizing the prototype, which can range from just an execution of a computer program to the actual building of a functional prototype. (Chua et. al 2010, 2)

Rapid Manufacturing: ”The use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as *finished products or components*” (Hopkinson, Hague & Dickens 2006, 1) The term additive manufacturing is sometimes used as a synonym for rapid manufacturing (Gibson et al. 2010).

Technology: There is no single, clear and universal definition for the term technology. Definitions for technology may vary from the point-of-view. For example the same definition of technology may not work for philosophers and engineers. (Spender 2010) In this research report technology is defined as a process by which an organization transforms labor, capital, materials, and information into products and services of greater value (Christensen 1997, xvi).

1.4 Structure of this research report

Following this Introductory Chapter, the following five Chapters were presented. Chapter Two introduced the methodology of the study and justified the methodological choices used in the empirical part of this research report. The Third Chapter provided the theoretical framework for the study. Relevant academic literature was reviewed on theories of disruptions and their adoption. In the Fourth Chapter the case used in this research report was described. Chapter Five described the empirical analysis and findings from primary and secondary data. The Sixth Chapter analyzed the rapid prototyping as a potentially disruptive technology. Then the possible effects of rapid manufacturing were discussed and conclusions were drawn based on the analysis and previous chapters.

2. Methodology

2.1 Qualitative single case study

This research report is conducted based on a qualitative single case study design. Qualitative research can constitute compelling arguments about how things work in a particular context (Mason 2002). The starting point of qualitative research is to describe real life. The reality is understood as subjective, which means that it is based upon perceptions and experiences that may be different for each person and change over time and context. (Eriksson & Kovalainen 2008) Typical features of qualitative research are: comprehensive collection of information from natural and real situations, people are preferred as the source of information, the use of inductive analysis, the use of qualitative methods in data gathering, selecting the unit of analysis by rationalizing instead of random sample, handling the cases as unique and interpreting the results accordingly (Hirsjärvi, Remes & Sajavaara 2009, 161-165).

This is an instrumental case study where the aim is to have an insight into a particular research question by studying a particular case (Stake 1995, 3). Here the single case is used to provide an insight on how rapid prototyping affects the design process and prototyping. According to Stake (1995, xi) a case study is expected to catch the complexity of a single case. It is a study of the particularity and complexity of a single case, coming to understand its activity within important circumstances. According to Hirsjärvi et al. (2009, 135) processes are typically in the interest of the case study, the data is gathered using several methods and the aim is to describe the studied phenomenon. In a single case study, the main objective is to understand that particular case well. The focus is on particularization, not generalization. (Stake 1995, 4, 8)

Professional literature and researches are reviewed with the intension of forming an understanding of the context of the study. The literature review is then complemented with the empirical findings of the single case study. The theoretical outcome of this research report can be labeled as suggestive theory building, which primarily offers a basis for further research.

2.2 Case selection

In this research report the case selection has evolved from a rather organic path. I was interested in researching the disruptive nature of 3D printing and rapid prototyping. At the time of planning of the research report, I was working as a consultant at the case company Outotec. I thought that rapid prototyping could have a significant impact on Outotec's business and thus I started to find out, if and how Outotec already used rapid prototyping. After meeting several different representatives, an opportunity to follow the progress of a just started design process, where rapid prototyping had been taken into use, was identified. I started to follow the progress of this design process in the phase, where a second prototype was produced.

2.3 Data collection

The empirical evidence of this research report was gathered from various different sources. Data for this research report is both primary data and secondary data. According to Eriksson & Kovalainen (2008, 77-78), the *primary data* is empirical data collected by researcher themselves. The primary data in this research report concerns the case data. This has been gathered mainly through interviews, but also some observations were made to support the interviews. The *secondary data* is already existing empirical data. As secondary data, previous literature and research reports were used to describe the design process, prototyping and rapid prototyping. The aim was to apply triangulation of data, where evidence is gathered from multiple empirical sources to cross-check information. (Eriksson & Kovalainen 2008, 292 - 293)

A chief engineer responsible for the new design was selected as a main source of the primary empirical data. He was selected as the source of information, because he could give the needed insight to the design process and prototyping as he made the design changes, conducted most of the tests and was in contact with rapid prototyping suppliers. Three interviews were held during the design and prototyping process. The first interview was held September 25, 2012 and lasted approximately 45 minutes. At this point the third prototype was ordered and the design process and prototyping was discussed until that point. The second interview took place October 23, 2012 and lasted approximately one hour. At this point all the planned tests with the third prototype were done and the plan was to make a larger series using injection molding. The third interview was held January 18, 2013 and lasted approximately 30 minutes. At that point the fourth prototype model was produced and it was going to the planned tests. In the third interview a possibility of a fifth prototype made with rapid prototyping was discussed, but the decision had not yet been made. If tests went well with the fourth and fifth prototype, the serial production would be started with injection molding.

Two phone interviews were held with the chief engineer after the third interview to make sure that the design process proceeded as discussed in the third interview. The written case description in Chapter *4.4 Description of the design process and prototyping of vacuum connection* was reviewed with the chief engineer and product manager involved in the design process on March 1, 2013 when the design process was at its end and the last prototypes were being ordered.

The interviews were held according to the positivist interview research approach, where interest is in the “facts”. This approach is suitable when studying “a process of organizational change”. Questions are formulated to collect information, which can give as accurate picture as possible of what happened in the process. (Eriksson & Kovalainen 2008, 79) I had looked into the literature concerning disruptive technologies, rapid prototyping and the design process used in this research report already before the interviews started. This familiarization formed the basis for the questions used in the interviews. The same interview questions, which can be found in appendix 1, were used as the basis for all of the interviews. All of the interviews were held at the Outotec office where the interviewed chief engineer worked. A separate meeting room was always reserved for the interviewees and the interviews were recorded and transcribed.

Also, observation was partly used in this research. I visited with the chief engineer, a rapid prototyping service provider, which was selected to produce the used prototypes starting from the third prototype. This allowed me to follow the discussions related to the material selection. This meeting was not recorded, but I kept notes from the meeting and the meeting was also discussed in the recorded interviews. These observations mainly supported the interviews and data from these observations is not used as empirical evidence in this research report.

2.4 Data analysis and interpretation

As a general analytical research strategy, this research report was based on theoretical propositions. In this research strategy, theoretical propositions that led to the case study were followed. Objectives and design of the case study was based on such propositions, which in turn reflect for example a set of research questions and reviews of literature. These kinds of propositions helped to focus attention to certain data and ignore other data. (Yin 2003, 111 – 116) Two propositions were guiding this research report. The first proposition was that rapid prototyping affects especially the design process and prototyping as rapid prototyping is used to make prototypes. The second proposition was that rapid prototyping needs to have some benefits, when compared against other methods and technologies used to produce prototypes for it to be a potentially disruptive technology. These propositions were made based on the literature concerning disruptive technologies, design process and rapid prototyping which were looked into at the beginning of this research.

The pattern matching technique was used to analyze the primary data from the interviews. In this technique, patterns are found from the empirical data which are then compared to the propositions pre-developed on the basis of existing theory. If the patterns coincide, the results can help a case study to strengthen its internal validity. (Yin 2003, 116 – 120) In this research report, the findings from the primary data (case interviews) were cross checked with findings from the secondary data (previous literature and research) and theory on disruptive technologies.

The analysis started by thoroughly reading the transcripts of the interviews. The units of analysis were arguments that the chief engineer provided as answers to the interview questions. The units of analysis were categorized according to the theoretical foundation and key research questions of this study. As patterns and analysis units started to emerge they were divided into categories. These categories where then compared to the pre-developed propositions from the secondary data. Arguments were used together with the findings from the secondary data in the empirical findings of this research report. The empirical findings were then reflected to the theory on disruptive technologies and results were described in the analysis and discussion of this research report.

2.5 Validation of the study

According to Hirsjärvi et al. (2009), accurate description of how the research has been conducted, enhances the reliability of a qualitative research. Circumstances of the data gathering should be explained in detail. For example, the places and the timings of the interviews and observations should be explained clearly. Also the time spent on interviews, possible distractions, misinterpretations and also the interviewer’s self-evaluation of the situation should be explained. According to Stake (1995), the case will never be seen the same by everyone involved. Thus discovering and portraying the multiple views of the case is important. Mason (2002) states, that the qualitative research should be *accountable* for its quality and its claims. Thus it should not attempt to position itself beyond judgment and should provide its audience with material upon which they can judge it. I have provided as much detail about the research process and methodology as possible, to meet these requirements for qualitative research. The circumstances of the data gathering were described in Chapter *2.3 Data collection* and the readers of this research report should be able to get the correct description of the data gathering process based on that.

This research report has relied mainly on one primary source of data related to the case, the chief engineer responsible for the re-design of vacuum connection at Outotec. To make sure that the case description in Chapter *4.4 Description of the design process and prototyping of vacuum connection* is accurate, its contents were post-checked with both the chief engineer and the product manager involved in the design process on March 1, 2013. Few changes were made to the case description according to the feedback received from the chief engineer and the product manager.

2.6 Limitations of the study

As this research report was conducted based on a qualitative single case study design, there are multiple limitations on the generalization of the results. The focus of qualitative research is in finding and revealing issues rather than to prove already existing statements. (Hirsjärvi et al. 2009). And the single case study aims to catch the particularity and complexity of a single case coming to understand its activity within important circumstances. (Stake 1995, xi) This research report is aimed to describe the nature of rapid prototyping as a disruptive technology and its impact on the design process in its full complexity in a single case. Further research is going to be needed to find out, if the results of this research report can be generalized to more than one case.

3. Theory on technology driven business disruptions

Foster (1986), Christensen (1997) and Utterback (1994) describe how the development of different competing technologies creates technological discontinuities that affect markets and industries. These technological discontinuities describe periods of change from one group of products and/or processes to another. The research on disruptive technologies started when researchers began to wonder why so many established market leaders' products often lost their position for companies that came to the market with new radical technology (e.g. Christensen 1997, Utterback 1994).

Technology can and has been defined in many different ways (e.g. Rosenbloom 2010, Christensen 1997, Rogers 1962). It can be a specific process, or in a broader definition it can be a general way a company does business or attempts a task. Many times there are multiple technologies used to produce a certain product, but also many times there are one or few technologies that are more crucial to a product or its production. (Foster 1986) Christensen (1997, xvi) defines technology as a process by which an organization transforms labor, capital, materials, and information into products and services of greater value.

Technology evolves as time passes and new development efforts are being made. According to Rosenbloom (2010) "*technology evolution* refers to changes in production processes or institutional arrangements that make it possible with a fixed set of resources to produce either (1) a greater quantity of a given product or service or (2) to produce new or qualitatively superior products or services".

The term *disruptive technology* was coined by Clayton Christensen and was widely popularized through his books The Innovator's Dilemma (1997) and Innovator's Solution (2003). According to Danneels (2004) disruptive technology "is a technology that changes the bases of competition by changing the performance metrics along which firms compete". Disruptive technologies can also be called "radical technologies" according to the categorization of “radical” and “incremental” technologies (Rosenbloom 2010; Garcia 2010). According to Rosenbloom (2010) technology evolves in these two distinct ways. It can evolve through gradual, incremental modifications in existing products and processes, or through discontinuous leaps in technology caused by the introduction of entirely revolutionary new technologies. Both kinds of evolution are needed and much of the impact of major revolutionary technologies would be far less dramatic without the accumulation of small improvements to the original technologies. Technologies are also many times interdependent on other technologies. For example lasers are used in a wide variety of applications and all of these applications are interdependent on the development of lasers. Thus disruptive technologies usually start with major revolutionary technology innovations, but achieve their disruptive nature with time and after many smaller improvements have been made to the original technology and interdependent technologies.

Sood and Tellis (2005) criticize the use of describing terms like “revolutionary” or “disruptive” for innovations, because they are intrinsically problematic as they define an innovation in terms of its effects rather than attributes. Thus they define technological change in terms of intrinsic characteristics of the technology. Sood & Tellis have identified and defined three types of technological change: platform, component and design. *Platform innovation* is the emergence of a new technology based on scientific principles that are distinctly different from those of existing technologies. *Component innovation* uses new parts or materials within the same technological platform. *Design innovation* is a reconfiguration of the linkages and layout of components within the same technological platform. Improved performance in the platform innovation results from innovation in component or design.

Another common categorization for disruptive technologies is the distinction between product innovations and process innovations. These will be described in detail in the following chapters. (e.g. Utterback 1994; Foster 1986; Thusman & Anderson 1986)

3.1 Competence-destroying and competence-enhancing technological shifts

Tushman and Anderson (1986) have researched patterns of technological change and impact of technological breakthroughs on environmental conditions. According to them technology evolves through periods of incremental change punctuated by technological breakthroughs.

Tushman and Anderson (1986) define technology as "those tools, devices, and knowledge that mediate between inputs and outputs (process technology) and/or that create new products or services (product technology)". They also divide major technological shifts into competence-destroying or competence-enhancing, because they either destroy or enhance the competence of existing firms in an industry. Technological changes can be categorized into four groups according to these dimensions (Figure 4).

		Technological shift	
		Competence-destroying	Competence-enhancing
Technology	Product technology	New product class OR Product substitution	Improvements in product
	Process technology	Process substitution	Improvements in production efficiency

Figure 4 A typology of Product and Process Technological changes (Adapted from Thusman & Anderson 1980)

Utterback (1994) adds to this typology the distinction of *assembled products* and *nonassembled products*. Most of the products are assembled from many parts. These are the everyday products we see around us (like televisions, automobiles, chairs etc.). Nonassembled products are products composed of only one or few materials (like paint, steel, glass etc.). Utterback notes that most competence-destroying product technologies almost always come from outside the industry. Most of the competence-destroying process technologies also come from outside the industry even though the distinction is not as clear as in product technologies.

3.2 The S-curve

Foster (1986) describes the relationship between the effort put into improving a product or process and the results one gets back for that investment as the S-curve (Figure 5).

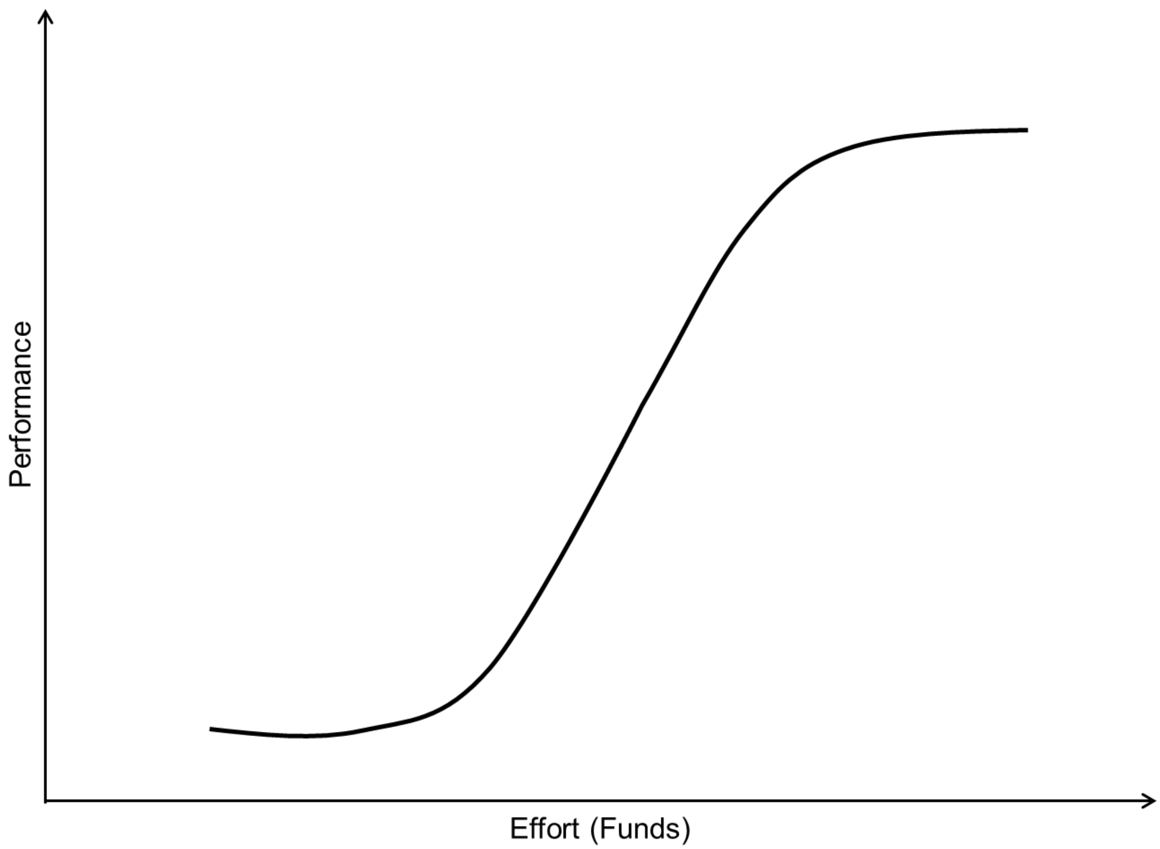

Figure 5 The S-curve: The infancy, explosion, then gradual maturation of technological progress (Foster 1986, 31)

At the beginning of developing a new product the progress is very slow (the bottom left part of the S-curve, the infancy). As the key knowledge necessary to make advances is put in place and more investments are put into the development of a product or a process the performance rises fast (the middle of the S-curve, the explosion). Achieving even further technical progress starts to become harder and harder at some point as technical limits are being reached (the top right part of the S-curve, the gradual maturation). Foster advises to identify the parameters for the Y-axis of performance for each group of product users, because each group of users has a different set of needs. The parameters must also be related to the key design factors of each specific technical approach. These performance parameters can and will change over time.

The S-curves almost always comes in pairs or more, because there are constantly several competing technologies each with its own S-curve. Foster uses the term discontinuity to describe the era when two or more competing technologies are in the market or industry. (Figure 6)

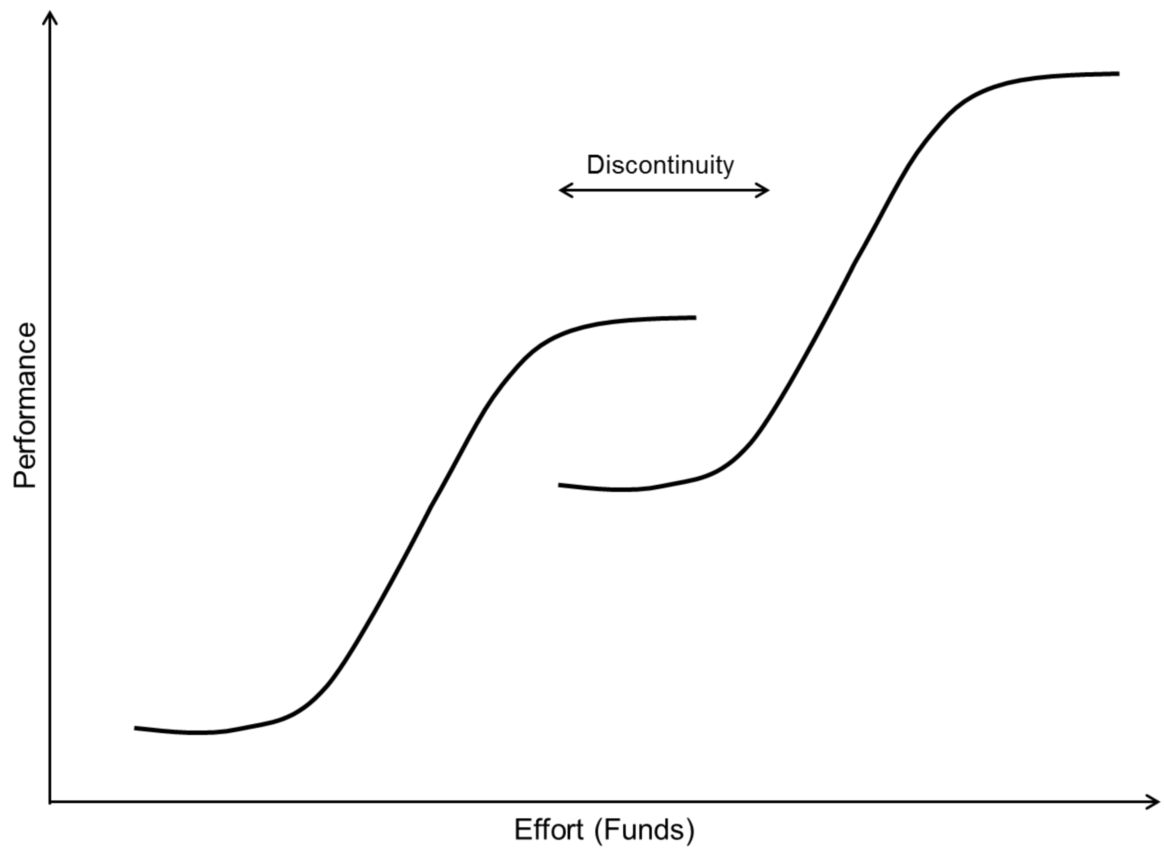

Figure 6 S-Curves Almost Always Appear in Pairs (Foster 1986, 102)

More recent research, conducted by Sood and Tellis (2005), shows that technologies do not show evidence of a single S-shaped curve of performance improvement. Rather, they evolve through an irregular step function with long periods of no growth in performance interspersed with performance jumps.” Also the paths of rival technologies may cross more than once or not at all and they may enter above or below the performance of existing technologies. Sood and Tellis (2005) also argue that new technologies come as much from new entrants as from large incumbents. All these are reasons why Sood and Tellis have criticized the suggestion that new technologies seem to evolve along the S-curve that intersects with old technology and ends above it.

3.3 Technological innovation and product innovation

Technological innovations have no market value, if they cannot be turned into sellable products (e.g. Kotler & Armstrong 2012). Chandy & Tellis (1998) define radical product innovation as the propensity of a firm to introduce new product that (1) incorporate substantially different technology from existing products and (2) can fulfill key customer needs better than existing products. Thus two dimensions which define radical product innovation are (1) technology and (2) markets. The first factor determines the extent to which the technology involved in a new product is different from prior technologies. The second factor determines the extent to which the new product fulfills key customer needs better than existing products. Four types of product innovations can be driven from these aspects. (Figure 7)

		Customer Need Fulfillment Per Dollar	
		Low	High
Neweness of technology	Low	Incremental Innovation	Market Breakthrough
	High	Technological Breakthough	Radical Innovation

Figure 7 Types of product innovation (Chandy & Tellis 1998)

These different types of innovations can be connected to the series of S-curves of technological innovation (Foster 1986). (Figure 8)

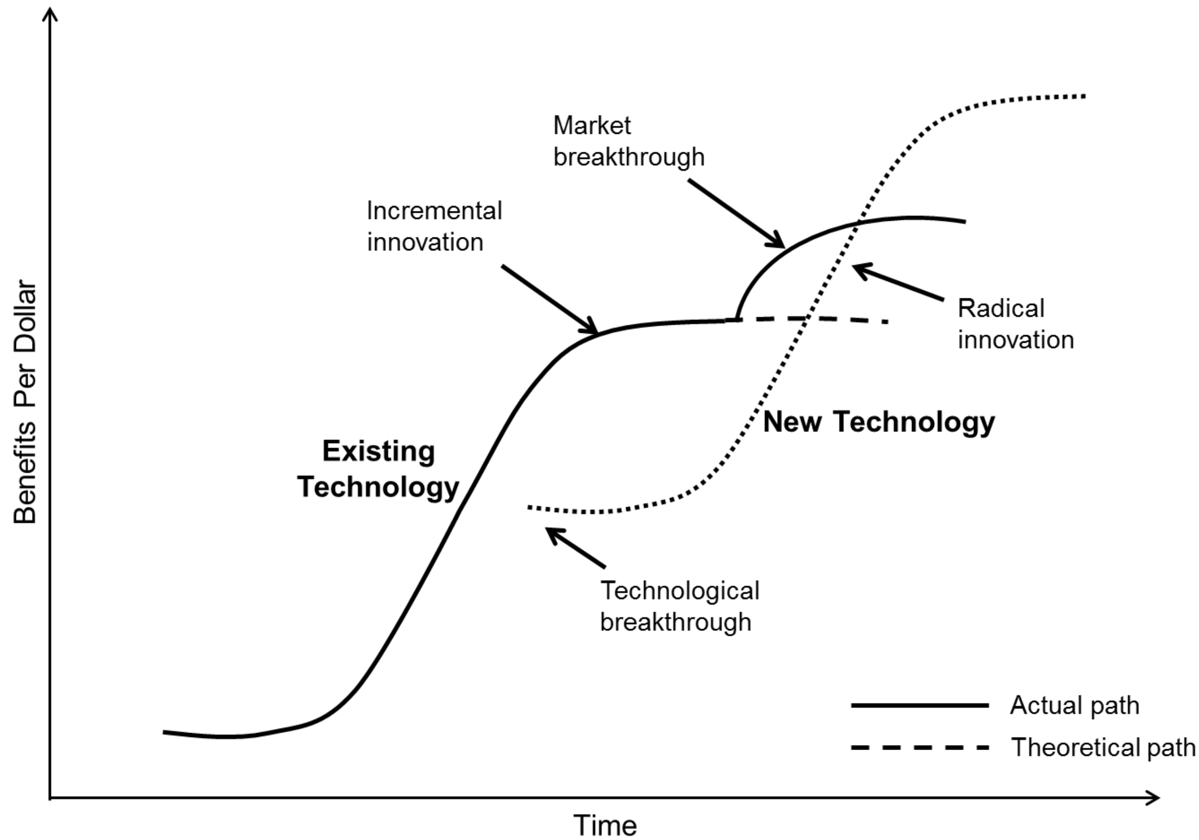

Figure 8 A dynamic view of product innovation (Chandy & Tellis 1998)

In Chandy's & Tellis's (1998) dynamic view of product innovation (Figure 8), the existing technology develops as a S-shaped curve like in Foster's (1986) model. At some point a new technology emerges with initially inferior benefits when compared to existing technology and it might be considered as a *technological breakthrough*. With research this new technology begins to improve rapidly in consumer benefits, and it ascends in its own S-curve. At the point where the new technology's benefits pass the existing technology's benefits, the product becomes a *radical innovation*. When faced with the threat, the supporters of existing technology make efforts to improve the benefits of existing technology. These efforts might yield some product improvements, which might represent a *market breakthrough* or just an *incremental innovation*. In the end the improvements of the existing technology cannot keep pace with the faster rise of the benefits in the new technology which ultimately replaces the existing technology as the dominant technology.

Also Utterback (1994) notes that established players that are using the old technology usually continue the investments to the older technology which results in a “burst of improvement in established technology” which is similar to the market breakthrough product innovation type that Chandy & Tellis (1998) have defined.

3.4 A dynamic model of an innovation in an industry

Utterback (1994) has researched the role of technological evolution and innovation in shaping the destinies of industries and firms. He has created a model of product and process innovation (Figure 9).

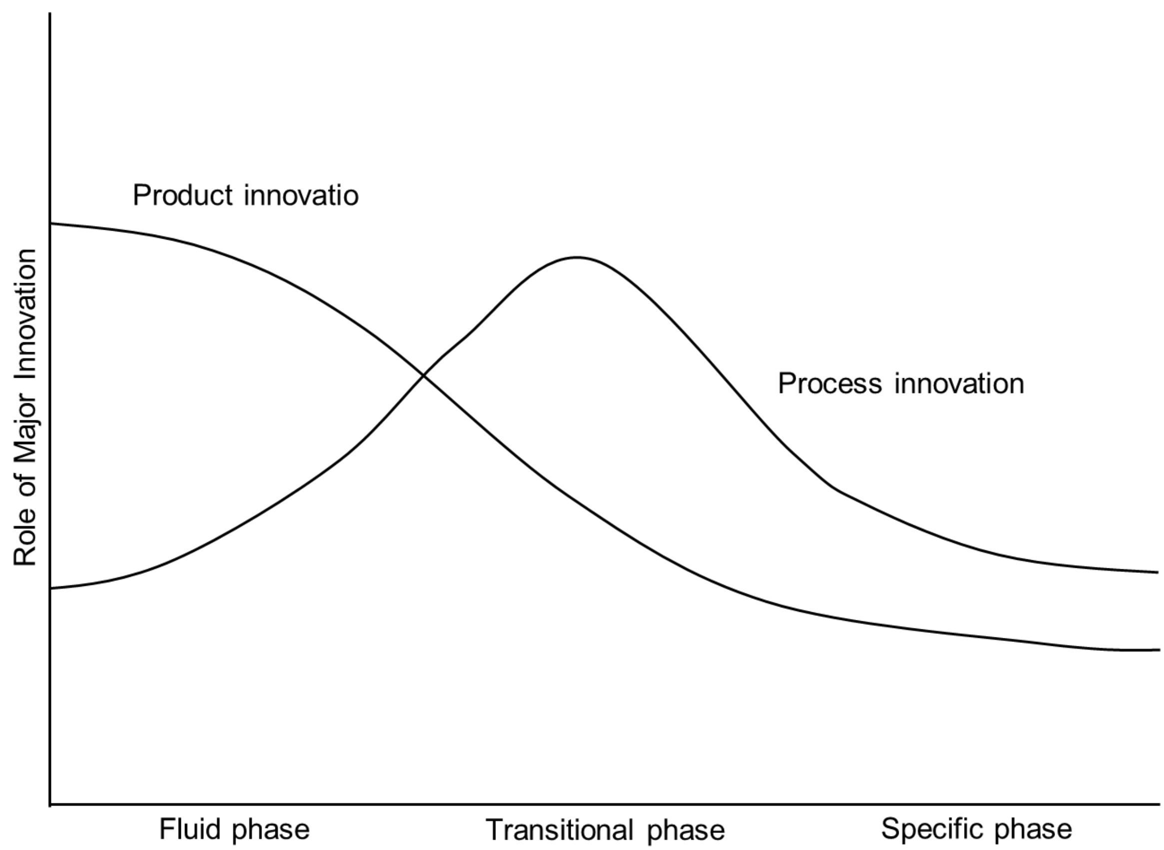

Figure 9 Model of product and process innovation (Utterback 1994, 124)

According to Utterback the rate of major innovation for both products and processes follow a general pattern over time, and product and process innovation share an important relationship. Developmental phases that technologies go through are fluid, transitional, and specific.

During the *fluid phase* the rate of product innovation in an industry or product class is the highest. A great deal of experimentation with product design and operational characteristics takes place among competitors. The processes that are used to make the products are given less attention at this phase. In the *transitional phase* the rate of major product innovation slows down and the rate of major process innovations speeds up. Standard and dominant designs start to arise. They are designs which have either proven themselves in the marketplace or designs that have been dictated by accepted standards, by legal or regulatory constraints. At some point *the dominant design* wins the allegiance of the marketplace and thus forces competitors and innovators to adhere, if they hope to succeed in the market. The pace of process innovation increases as the form of a product becomes more settled. Some industries enter the *specific phase* where the rate of major innovation decreases for both product and process. Focus turns to cost, volume and capacity and there are only small and incremental product and process innovations.

As a summary, the product moves from high variety, to dominant design and finally to incremental innovation on standardized products. The manufacturing process progresses at the same time from heavy reliance to skilled labor and general-purpose equipment to specialized equipment tended by low-skilled labor.

Utterback concludes that most technology-based innovations are in fact part of a continuum of change in a very similar matter as Foster’s (1986) parallel S-curves. Each wave of innovation repeats the pattern of interlinking product and process innovation. The terms that Utterback uses to describe these waves are established product and invading product. A radical technological innovation can emerge and successfully invade and eventually overwhelm the established technology in almost any circumstance.

3.5 Technology cycle

Combining the elements from Foster’s (1986) S-curve and Utterback’s (1994) model of product and process innovation, Anderson & Tushman (2004) describe a *technology cycle*. (Figure 10)

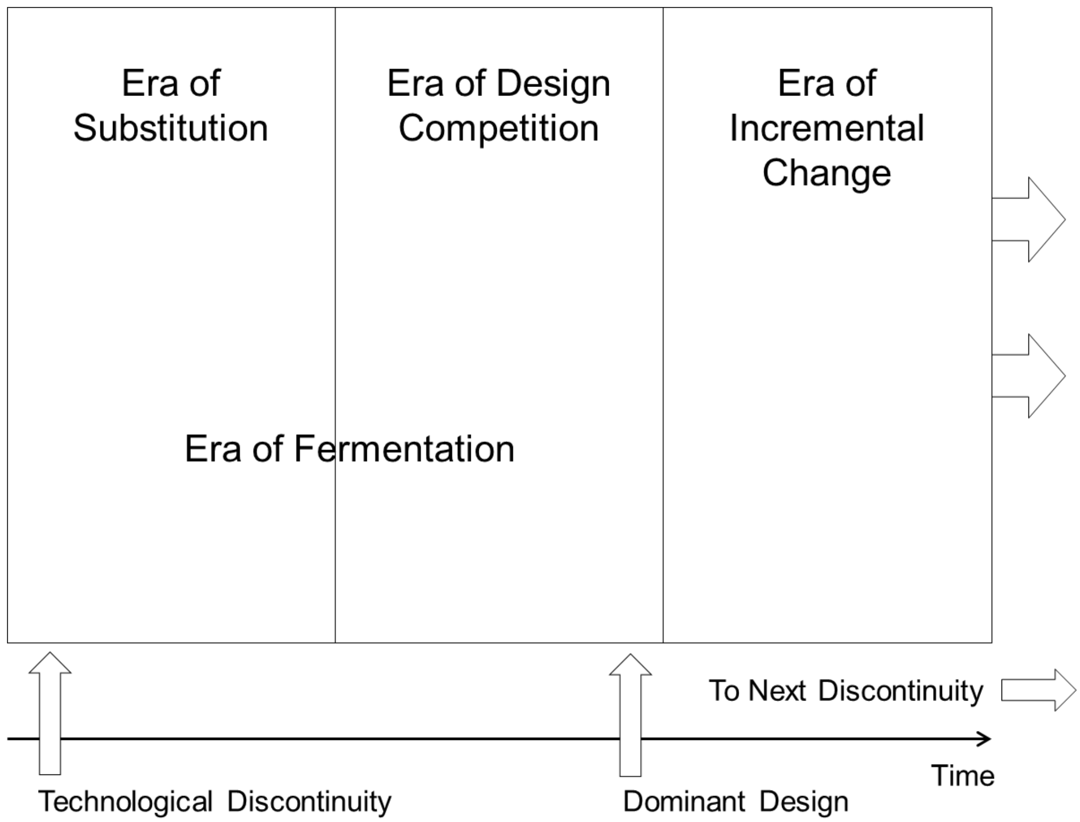

Figure 10 Technology cycle (Anderson & Tushman 2004)

Foster's (1986) notion of a series of S-curves suggests that an industry evolves through a succession of technology cycles and each cycle begins with a technological discontinuity. These are breakthrough innovations that are technologically better in economically relevant dimensions of merit. Anderson & Tushman (2004) state that the breakthrough innovation initiates an era of fermentation, which is characterized by two processes. First is the *era of substitution* when new technology displaces its predecessor. During this era, often the old technology also improves significantly in response to the competitive thread, but eventually new technology displaces the previous technology. The second process, the *era of design competition*, overlaps partly with the era of substitution. Here the initial radical innovation is usually replaced by more refined versions. Typically, several competing designs emerge. The design competition culminates in the appearance of a dominant design that Utterback (1994) has described. The dominant design moves the focus of competition to market segmentations and lowering costs via design simplifications and process improvements.

This marks the *era of incremental change* which continues until the next technological discontinuity emerges to start the next technology cycle.

3.6 Technology adoption lifecycle

Rogers (1962) has researched the diffusion of innovations. He defines *diffusion* as "the process by which an innovation is communicated through certain channels over time among the members of a social system". Rogers makes the note that many of the new innovations are technological innovations. He describes the rate of adoption of an innovation as the bell shaped frequency curve that approaches normality and defines five adopter categorizations on the basis of innovativeness. Moore (1991) has utilized the work of Rogers and developed a Technology Adoption Lifecycle model to help marketers understand how high-tech markets evolve and how to cross the chasm, meaning making the mainstream market for high-tech products emerge. The model describes the market penetration of any new technology product in terms of progression in the types of consumers it attracts throughout its lifecycle. (Figure 11)

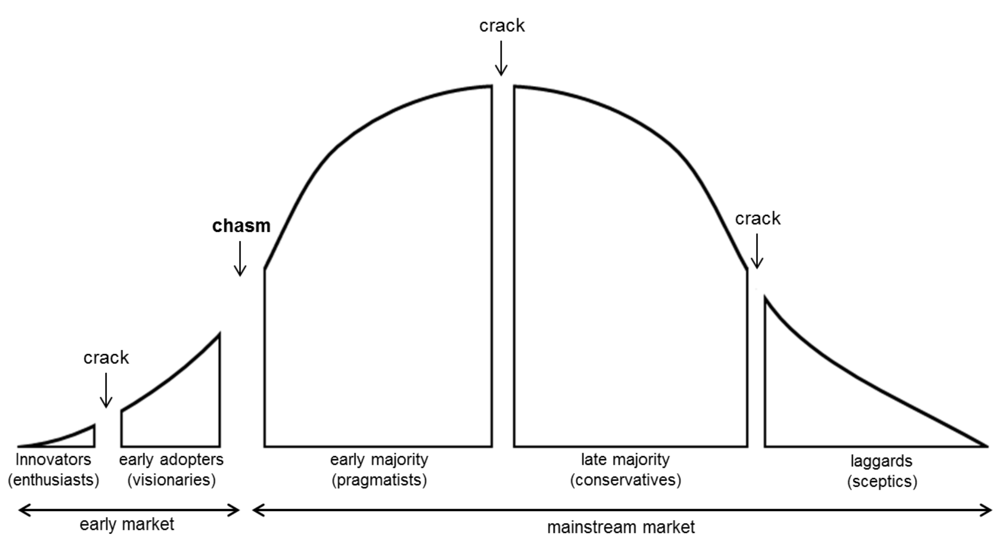

Figure 11 Technology adoption lifecycle (Moore 1991)

The divisions in the curve are roughly equivalent to where standard deviations would fall. The groups are distinguished from each other by their characteristic response to a discontinuous innovation based on new technology. Each group represents an unique psychographic profile, which is a combination of psychology and demographics that makes its marketing responses different from those of the other groups.

Innovators pursue new technology products aggressively. Technology is a central interest in their lives and they seek the newest technology even before formal marketing of it has been started. Innovators are a small, but important group, because their endorsement reassures other players in the market that the product actually works. *Early adopters* also buy into new product concepts early in their life cycle. Early adopters find it easy to imagine, understand, and appreciate the benefits of a new technology and relate these potential benefits to their own concerns. Early adopters do not need well-established references, but they rely on their own intuition and vision. This is why they are the key in opening up any high-tech market segment. *The early majority* is driven by a strong sense of practicality. They want to wait and see well-established references before investing substantially. The early majority represents roughly one-third of the whole adoption life cycle and thus winning their business is key to any substantial profits and growth. *The late majority* shares all the concerns of the early majority and they have one major additional one. People in the early majority are comfortable with their ability to handle a technology product, but people in the late majority are not. This is why the late majority waits until something has become established as a standard. They want lots of support and that is why they purchase from large, well established companies. Finally comes the *laggards* who do not want to do anything with new technology, because of a variety of different personal reasons. The only way they buy a technological product is when the technological part is integrated to the product in a way that they do not know it is even there.

Between each of these groups there is a gap, which symbolizes the disassociation between the two groups. This means the difficulty any group will have in accepting a new product, if it is presented in the same way it was to the group to its immediate left. According to Moore the biggest challenge is to cross the gap between the early adopters and the early majority which he calls the *chasm*. The chasm is created by the differences in how these two groups approach new technologies and how they form their decisions on whether or not they will adopt them. The early adopters expect to get a jump on the competition and radical discontinuity with the old ways and the new. They understand that being among the first means that there will be bugs and glitches that they need to be prepared for. The early majority are looking to buy productivity improvement for existing operations. In contrast to early adopters they are looking to minimize the discontinuity with the old ways. They want evolution instead of revolution. By the time they are ready to adopt a new technology, they want it to work properly and to integrate appropriately with their existing technology base. This is why consumers belonging to the early majority want references from others in the early majority, not from the early adopters as their interests are so different.

Moore's advice to cross the chasm is to target a very specific niche market somewhere in the early majority and force the competitors out of that niche, and then use it as a base for broader operations. Thus the aim is to identify a small niche of the early majority and create a full "whole product" offering that works as an answer to their demand which was described above. After this niche has been gotten as a reference, it is much easier to expand to other customers in the early majority.

3.7 Sustaining and disruptive technologies

Christensen & Raynor (2003, 31-47) describe with their disruptive innovation model how innovations enter and affect the markets (Figure 12). They separate technologies into two categories. There are sustaining technologies and disruptive technologies. *Sustaining technologies* foster improved product performance. They improve the performance of established products along the dimensions of performance that mainstream customers in major markets have historically valued. Sustaining technologies target demanding, high-end customers. *Disruptive technologies* result in worse product performance at least in the near term and bring to a market a different value proposition than had been available previously. They are typically cheaper, simpler, smaller and frequently more convenient to use. Disruptive technologies usually have features that new customers value, but as the performance attributes that customers value improve at a rapid rate, the new technology can invade established markets. These kinds of disruptions are called *low-end disruptions* in the disruptive innovation model.

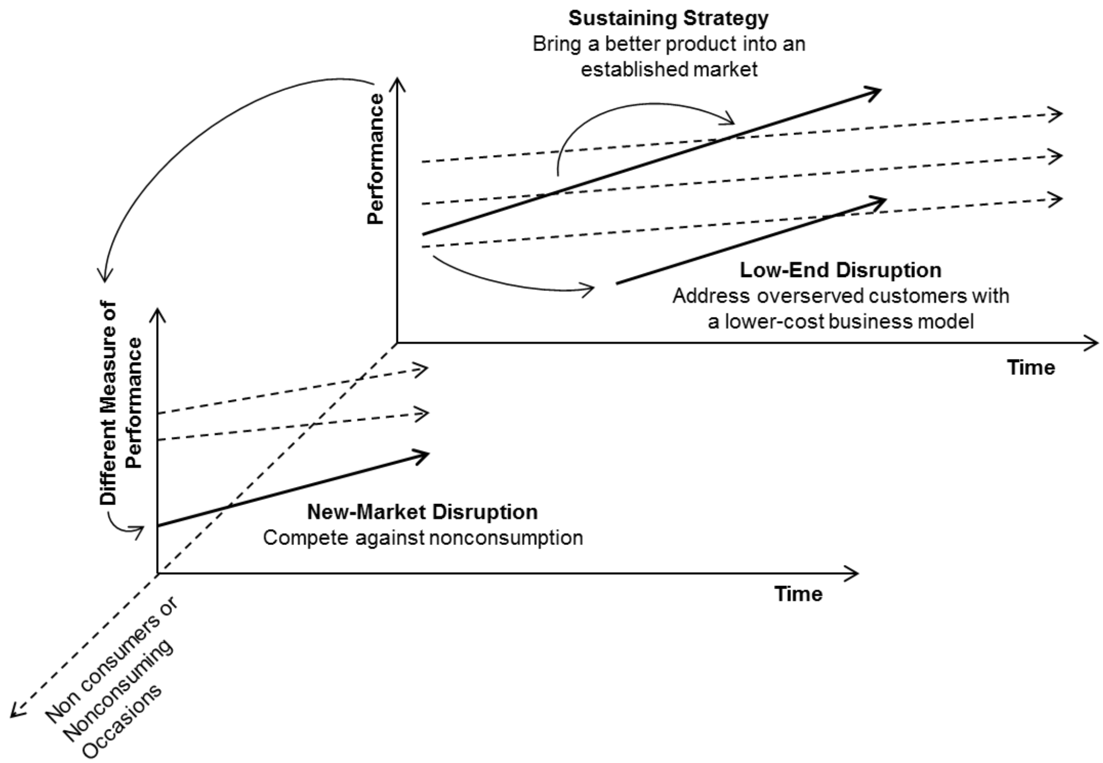

Figure 12 Disruptive Innovation Model (Christensen & Raynor 2003, 44)

The third axis in the disruptive innovation model represents new customer and new contexts for consumption. This dimension, which is called *new-market disruption*, competes with “nonconsumption”, as “new-market disruptive products are so much more affordable to own and simpler to use that they enable a whole new population of people to begin owning and using the product, and to do so in a more convenient setting.”

Different technological innovations have different performance trajectories on a given industry. Performance trajectory is the rate at which the performance of a product has improved and is expected to improve over time. Different industries have different critical performance trajectories. For example in disk drives one crucial measurement of performance is storage capacity. (Bower & Christensen 1995) Relevance and competitiveness of different technological approaches can change with respect to different markets over time, because the pace of technological progress can outstrip what markets need (Christensen & Raynor 2003).

Utterback & Acee (2005) have criticized Christensen's definition of "disruptive technologies", because it emphasizes only "attack from below" and ignores other discontinuous patterns of change. They present an alternative scenario where higher performing and higher priced innovation is introduced first into the most demanding established market segments and later moves towards the mass market. In their analysis they consider three variables of competitive advantage due to technological change. These are cost, traditional performance and ancillary performance. For example, at first, digital cameras had more expensive technology with lower traditional performance, but higher ancillary performance for editing, storing and transmitting images. Thus digital photography was first in use in the most demanding customers and as costs rapidly declined, the use of digital photography moved to mass markets. According to Utterback and Acee the true importance of disruptive technology is in its powerful means for enlarging and broadening markets and providing new functionality. Also Tellis (2006) and Danneels (2004) have criticized Christensen's definition of disruptive technology. According to them Christensen does not provide clear-cut criteria to determine whether or not a given technology is considered as disruptive.

3.8 Big-bang disruptions

Recently Downes and Nunes (2013) introduced a new kind of disruption that they call *big-bang disruption*. They also criticize Christensen's disruptive innovation model for assuming that disruptions start with lower-priced and inferior alternatives, which gives an incumbent business time to generate its own next generation products. They argue that now entire product lines and whole markets are being created and destroyed "overnight". Example of this kind of big-bang disruption is navigation apps in smartphones which have disrupted the markets of navigation product makers like TomTom and Garmin. This and other examples of big-bang disruptions given by Downes and Nunes relate to the information based goods and services or to the use of information technology in physical products.

Three common features for the big-bang disrupters are unencumbered development, unconstrained growth, and undisciplined strategy. *Unencumbered development* refers to the ability to experiment with new applications at little risk to investors and abandoning the prototypes that do not quickly prove popular. These experiments can take place directly in the market, using open platforms built on the internet, cloud computing, and fast-cycling mobile devices. *Unconstrained growth* collapses the product lifecycle as Rogers (1962) and Moore (1991) has described it. This can happen, because the big-bang disruptions can be marketed to every segment simultaneously, right from the start. The two customer segments left are trial users, who often participate in product development, and the vast majority representing everyone else. Downes and Nunes also argue that a new development cycle can be simplified into three basic stages: development, deployment, and replacement. By *undisciplined strategy* Downes and Nunes argue, that big-bang disruptions challenge the conventional thinking of for example Treacy's and Wierseman's (1995) three value disciplines. According to Treacy and Wierseman (1995) companies should align their strategic goals along one of the three value disciplines: low cost (operational excellence), constant innovation (product leadership) or customized offerings (customer intimacy). Big-bang disrupters are undisciplined and start with better performance, lower price, and greater customization. Thus they compete in all three disciplines right from the start.

3.9 Summary of technology driven business disruptions

As a summary of the literature, first different definitions of disruptive technology are summarized. Four models were introduced, which relate to the evolvement and development of disruptive technologies which seem to have three main phases during the lifecycle of a single technology innovation. These are summarized after the definitions of disruptive technology.

3.9.1 Definitions of a disruptive technology

Foster (1986) suggests that the parameters for the y-axis of performance of the S-curve should be identified separately for each group of users, because each group has a different set of needs. Thus measuring performance improvements in features that clients do not appreciate would lead to false assumptions about the disruptiveness of the technology. Also Chandy and Tellis (1998) note that radical innovations need to use radically new technologies, but they also need to fulfill key customers' needs better than existing products. Anderson & Tushman (2004) state that breakthrough innovations are technologically better in economically relevant dimensions of merit. This can be interpreted that economically relevant dimensions are the ones that customers are willing to pay for. Also Christensen & Raynor (2003) define disruptive technology as a technology that has attributes that customers value. Danneels (2004) highlights the new metrics that customers value as he defines disruptive technology as a technology that changes the basis of competition by changing the performance metrics along which firms compete. According to Utterback and Acee (2005) the true importance of disruptive technology is in its powerful means for enlarging and broadening markets and providing new functionality. To broaden the markets, new functionalities need to be appreciated by the customers. Thus many models describing the development of disruptive technologies acknowledge that the performance metrics are relevant in defining a disruptive technology. They also conclude that these metrics are defined by the customers and their needs.

The metrics that customers value can also change over time. The metrics might be totally new like in the case of new-market disruption where products become so much more affordable and simple to use, that totally new markets are created with new metrics relevant and specific for that market. In the low-end disruptions, a disruptive technology brings a critically lower price compared to the traditional metrics of the market. At the same time these technologies usually have features that new customers value so their performance is measured in different metrics from the new customers' point-of-view. (Christensen & Raynor 2003) But as the performance of a disruptive technology starts to improve, it can invade markets where a new set of customers value the enhanced performance. These changes can also create challenges for the marketers, because as Moore (1991) explains, it is challenging for a company to change their offering to serve a new customer type or group in the technology adoption lifecycle.

3.9.2 Three phases of disruptive technology

Four models (Rogers 1962, Foster 1986, Utterback 1994, Christensen 1997) were introduced, which relate to the development of disruptive technologies. These models can be found to evolve in three main phases during the lifecycle of a single disruptive technology innovation. For example Utterback 1994 concludes that most technology-based innovations are in fact part of a continuum of change in a very similar manner as Foster's

(1986) parallel S-curves. Here I have summarized the three phases of disruptive technology. (Figure 13)

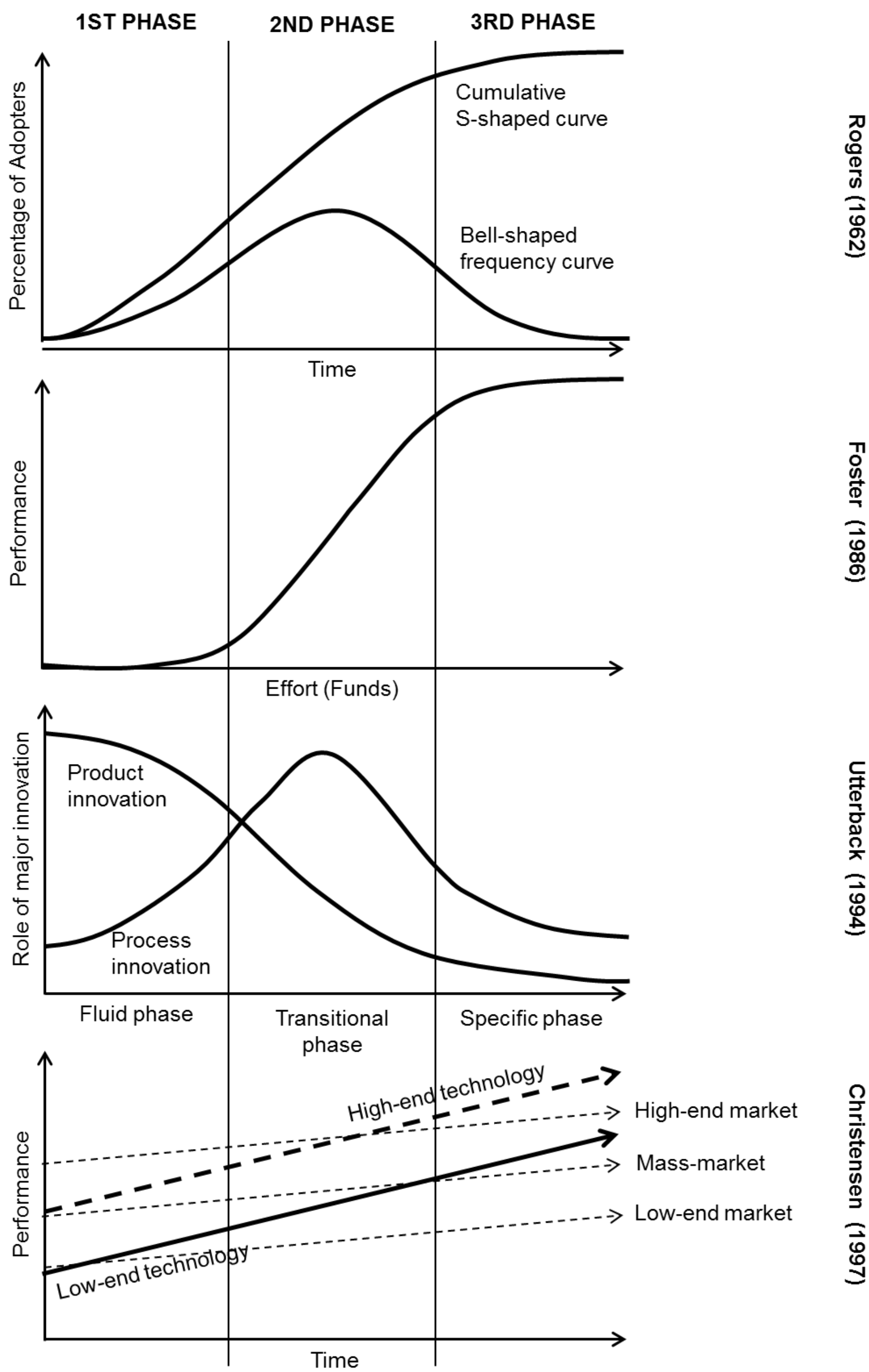

Figure 13 Three phases of disruptive technology (c.f. Christensen 1997, Utterback 1994, Foster 1986, Rogers 1962)

In the *first phase*, when a new technological breakthrough emerges, the development of a new technology is very slow (Foster 1986, Chandy & Tellis 1998). This is a fluid phase in Utterback's (1986) model of product and process innovation. In the fluid phase the focus is on experimentation around the product design. The processes that are used to make the products are given less attention. According to Christensen (1997), the new disruptive technology usually results in a lower performance than existing technologies, but still has features that new customers in low-end markets value. These customers can be innovators and early adopters, who are usually the first customer groups to take the new technology into use as they are the two groups that are excited about almost any new technology and are able to understand them without previously proven references (Rogers 1962, Moore 1991). These customer groups still represent a small fraction of the potential overall markets.

During the *second phase* of the disruptive technology's lifecycle more investments are being put to the development of the technology (Foster 1986). This is a transitional phase in Utterback's (1986) model of product and process innovation. In this phase standard and dominant designs start to arise. In the end dominant design wins the allegiance of the market place. The pace of process innovation increases as the form of a product becomes more settled. During the second phase a new customer group of the early majority needs to be reached and that means crossing the chasm (Moore 1991). Moore advises to select a small niche market where the new technology can be sold as a practical and working full product offering. Reaching the early majority is needed to move the disruptive technology from low-end market to the mass-market where existing technology is still sold (Christensen 1997). The existing technology might respond to the threat from the disruptive innovation by developing the technology further and increasing the benefits for customers in the form of a market breakthrough, but ultimately the new disruptive technology replaces the existing technology as the dominant technology in the mass-market (Chandy & Tellis 1998; Christensen 1997).

In the *third phase* disruptive innovation has reached the mass markets. Also the late majority of the customers start to use the technology. They have waited for the new technology to become an established standard in the market and lots of support is available

(Moore 1991, Rogers 1962). The majority of the customers have adopted the technology and the development progress starts to become harder as the technical limits are being reached (Foster 1986). In Utterback's (1994) model of product and process innovation, this is a specific phase, where focus turns towards cost, volume and capacity. Also according to Utterback the product and process innovations are small at this phase. Even though the development of the technology is slow at this phase, the performance of the technology can still improve above what most of the customers need. Thus there is a possibility for a new low-end disruptive technology to attack the markets and challenge the performance of the existing technology (Christensen 1997).

4 Case description

In this Chapter the case is presented by describing the case company Outotec, Outotec Larox CC filter and its vacuum connection in short. Then the design process of the vacuum connection is described.

4.1. Outotec Oyj

Outotec is a global leader in minerals and metals processing technology. Outotec also provides solutions for industrial water treatment, the utilization of alternative energy sources and the chemical industry. (Source: Outotec Oyj website <http://www.outotec.com/en/About-us/>). Outotec was formed, when Outokumpu Technology was organized as a legal consolidated group in 2006 and later in April 2007, according to the agreement made with the former parent company Outokumpu Oyj, it changed its name to Outotec. (Source: Outotec Oyj website < http://www.outotec.com/en/About-us/History/ >). Two of Outotec's core values are aspiring for excellence and creating leading technologies (Source: Outotec Oyj website < http://www.outotec.com/en/About-us/Our-values/>). Outotec's business is based on a strong portfolio of world-class technologies and robust expertise. (Outotec Oyj website <http://www.outotec.com/en/About-us/Research-and-technology/>) According to Treacy's and Wierseman's (1995) "value disciplines" distinction, Outotec's competitive advantage comes from its product leadership. The focus is on being creative, commercializing ideas quickly and constantly pursuing ways to leapfrog their own latest products or services.

4.2 Outotec Larox CC, Capillary Action Disc Filter

Outotec Larox CC filters are used to filter feed slurries with consistent, high solids concentration e.g. base metal concentrates, iron ore, chromite and ferrochrome. (Figure 14) See appendix 2 for Outotec Larox CC operating principles.

Figure 14 Outotec Larox CC Filter (Source: Outotec Larox CC Brochure)

4.3 Vacuum Connection

The vacuum connection is connected to the filtration disc in the Outotec Larox CC Filter (Figure 15). There are fifteen ceramic sections in the Outotec Larox CC. The vacuum connection connects the piping to the filter section. During the filtration, the flow is through the disc to piping. During the backflow washing the flow is the other way around.

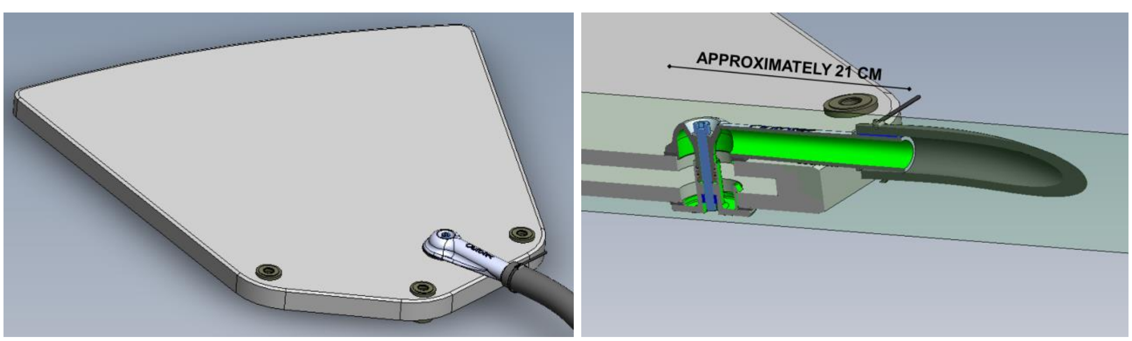

Figure 15 Outotec Larox CC Filter's vacuum connection installed to the disc (CAD images of 4th generation prototype)

4.4 Description of the design process and prototyping of the vacuum connection

Here the prototyping process of the vacuum connection is described. A summary of the case can be found in appendix 3. The process is divided according to the different prototypes and 3D CAD models made. The different 3D CAD models and prototypes are numbered according to their sequence. There have been many different 3D CAD models between different produced prototypes, but here all the changes made to the design between the prototypes are being described as a single CAD model. The different prototypes that are made by using rapid prototyping technologies are referred to as generations. This is the term that the chief engineer also used to describe the development of the prototypes. This description is based on the interviews held with the chief engineer making all the 3D CAD models. All the technical details are not described, because they are not in the focus of this research report.

Need for new design and first concept design

Outotec Larox CC's vacuum connection's old design (Figure 16) has a complex construction with 16 different parts and it has been noted that the old design is vulnerable to leaks, expensive and not optimized according to the liquid flow. Because of these issues, the product manager started the development of the vacuum connection design. The first concept design of the new design was made using metal and workshop based fabrication techniques. The idea at the beginning of the process was to use metal also as the end material, not just in the prototypes.

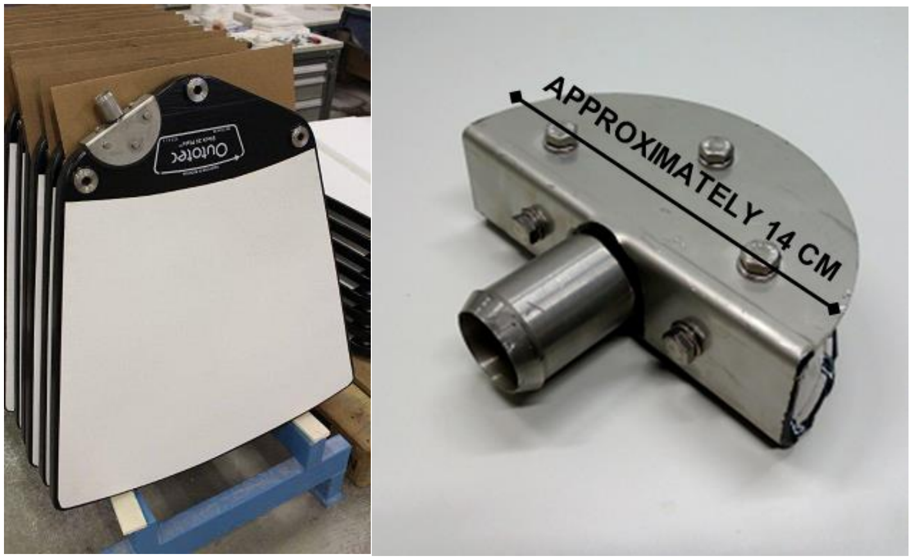

Figure 16 Old design of the Outotec Larox CC Filter’s Vacuum connection

1^{st} generation prototype

The first 3D CAD model was produced based on the first concept design which was made from metal. The product manager had been introduced to rapid prototyping when he visited the Saimaa University of Applied Sciences (SAIMIA). The first prototype was decided to be produced at SAIMIA using the SLS technique. This 1^{st} generation prototype was printed to get the first look and feel of the new design and to see, if there is potential in the new design. No one in the project had previous experience with rapid prototyping before the project started.

2^{nd} generation prototype

On the second CAD model corrections to the measures were made. Correct o-ring gasket sizes were tried and bolt lengths were optimized. Also, this prototype was printed in SAIMIA. This 2^{nd} generation prototype was installed and bolted to the disc. This showed that the needed fit was achieved.

3^{rd} generation prototype

After the fit had been found to be working the focus was turned to flow functionalities of the vacuum connection. The 3^{rd} 3D CAD model was tested several times with virtual flow tests and the design was changed according to the findings. (Figure 17)

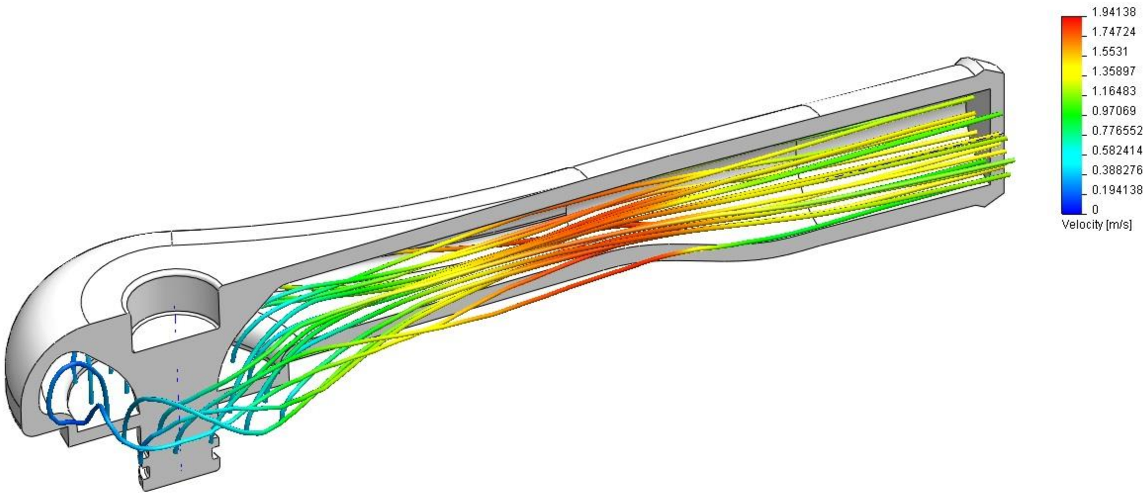

Figure 17 Image of one of the results from virtual flow tests

The next phase was to have real physical flow tests with the produced 3rd generation prototypes. At this point SAIMIA could not promise that the SLS machines they had in use could produce waterproof prototypes. The search started for a new supplier, which could produce printed prototypes with the needed features. The chief engineer and I visited one supplier and discussed different options for the correct prototype materials. Ten different material samples were obtained from the supplier. After examining the strength and other features of different materials, three samples were sent to Lappeenranta University of Technology (LUT) for testing. The material used for prototypes needed to be acid resistant, because the vacuum connection is in contact with acids when in use. One of the tested materials perished significantly when held in acid so the final material was selected from the two others that were also tested. Five copies were printed. Two of them were printed without infiltration and three of them were infiltrated to make them more water resistance.

Installation to the disc was tested with two prototypes without infiltration. The infiltrated ones were tested for flow resistance and misuse by trying to install them incorrectly and by trying to break them by bending. No problems occurred in these tests. There were also physical flow tests and pressure tests were conducted and the results were good. The flow performance was improved when compared to the old design. The only needed change noticed in the tests, was that at the pressure test surface connected to the disc deformed slightly when tightened firmly. This was corrected to the 4th 3D CAD model by adding one millimeter (25% more) to the thickness of this section.

As everything seemed to be like expected, the decision was made that a larger series of prototypes would be produced and put to test in a real situation in one of the customer's Outotec Larox CC machines. A series of approximately one hundred pieces was aimed to be manufactured. At this point it was noticed that rapid prototyping technologies were no longer the best choice. As the series size grew from a few pieces to a hundred pieces, the cost per prototype made with rapid prototyping rose over the cost of using injection molding for manufacturing. This is why suppliers of injection molded parts were contacted. The feedback from the suppliers of injection molding was that the vacuum connection could not be manufactured using the plastic injection molding, because the design of the 3rd generation prototype was such, that central cores used in the injection molding could not be removed after injection.

4th generation prototype

As the 3rd generation prototype could not be manufactured using injection molding a new design was performed. This design was done in co-operation with one of the suppliers of the injection molding. Five copies of the 4th generation prototype were printed after the correct design was found (Figure 18). They were tested first at one of the Outotec Larox CC machine in Outotec's own factory to make sure they still fitted and functioned like expected. Then three of them were installed to one customer's machine to make sure they worked in a production environment. Positive feedback was received from the mechanics who installed the prototypes.

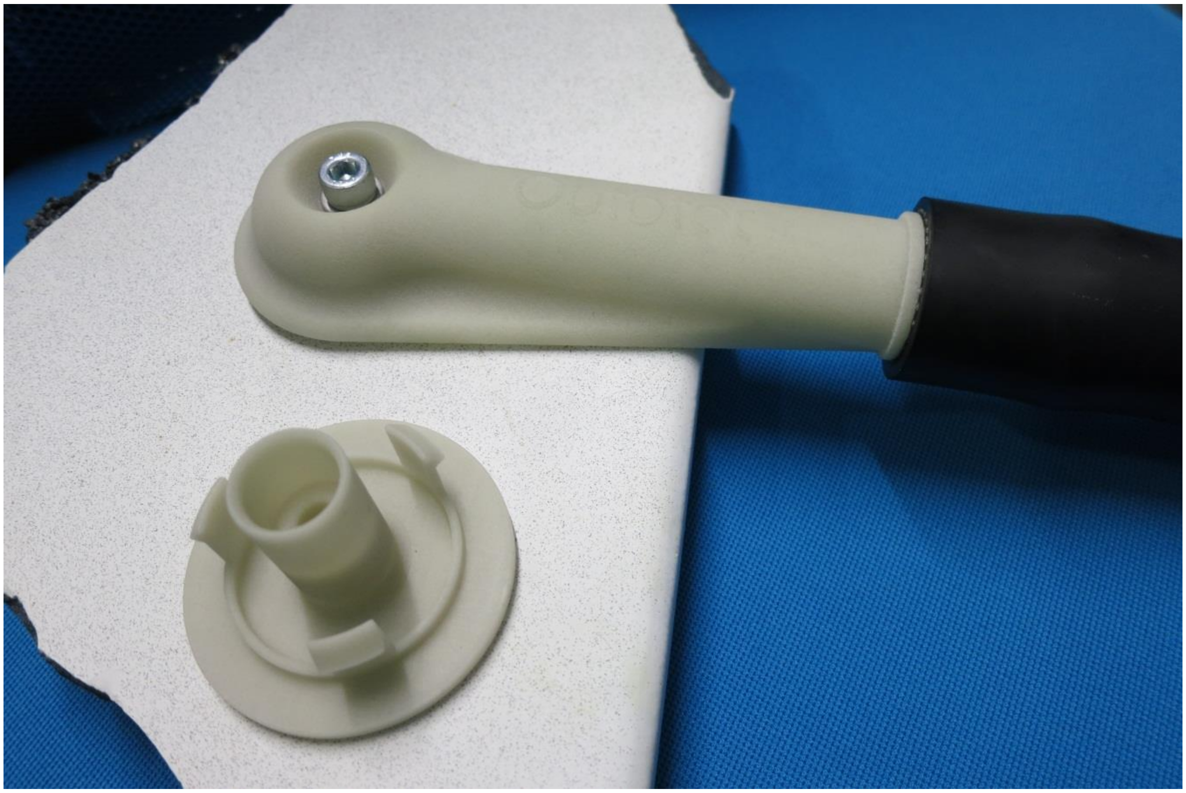

Figure 18 Picture of 4^{th} generation prototype connected to the sample disc and the hose

5^{th} generation prototype

It was noted that when connecting the hose to the 4^{th} generation vacuum connection prototype, the hose needed to be bent a bit more than with the old design of the vacuum connection. This was corrected in the 5^{th} 3D CAD model by shortening the design by a couple of centimeters. Five copies of the 5^{th} generation prototype were printed. Three of them were installed to the same customer's machine as the 4^{th} generation prototypes to make sure one last time that everything worked like expected in production environment.

Larger series done with injection molding

A short-run production of vacuum connections was needed to change all of the vacuum connections in one or more Outotec Larox CC filters. In this way the new design was able to be tested in a real production environment and in full-scale, before moving to a final production. At this point injection molding was selected as the manufacturing technology, because the cost per vacuum connection became lower this way and longer lasting materials were available.

5 Empirical analysis and findings

In this Chapter the design process, prototyping and rapid prototyping are first described. Then the benefits and limitations of rapid prototyping are compared against other technologies and methods used to produce prototypes.

Findings from the primary data (interviews) and the secondary data (previous literature and research) are cross checked with each other where applicable. Thus triangulation of data, where evidence from multiple empirical sources is used to cross-check information, is applied (Eriksson & Kovalainen 2008, 127, 292 - 293).

Quotations from the interviews are added in *italic font*. They are used to show how the interviewed chief engineer expressed some of the findings. The interviews were held in Finnish, which was the chief engineer's native language. I have done the translations of the quotations to English.

5.1 Prototypes

Prototypes play several roles in the product development and design process. These include for example experimentation and learning, testing and proofing, communication and interaction, synthesis and integration, scheduling and markers (Chua et al. 2010, 4).

The general definition of the prototype contains three aspects of interest (Chua et al. 2010, 2-4):

1. The implementation of the prototype; from the entire product (or system) itself to its subassemblies and components
2. The form of the prototype; from virtual prototype (that are nontangible) to a physical prototype
3. The degree of approximation of the prototype; from very rough representation to exact replication of the product

Rapid prototyping falls within the range of physical prototypes which is shown as the shaded volume in Figure 19.

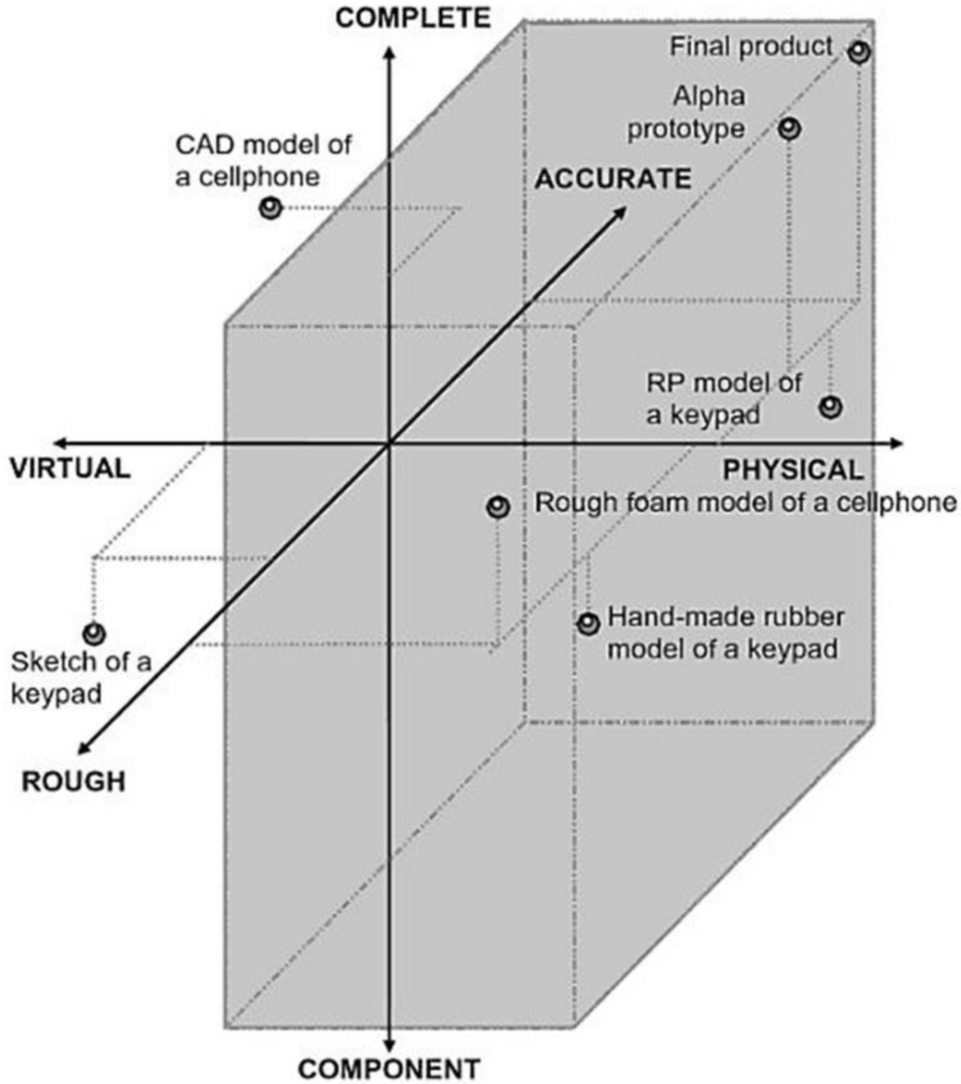

Figure 19 Types of prototypes described along the three aspects of approximation, form and implementation (Chua et al. 2010, 5)

Prototypes are made to test the product's or part's form, fit and function during the design process. *Form* means the shape and general purpose of the product, *fit* means the appropriate tolerances required for assembly purposes and *function* means the eventual way a product or a part will work. (Gibson et al. 2010, 3)

The vacuum connection prototypes were examples of prototypes which are needed to study or investigate special problems associated with one component, subassemblies or simply a particular concept of the product that require close attention. They were accurate physical models of a component. In this case prototypes had a role in the product development process as experimentation, testing, communication and synthesis. (Chua et al. 2010) Prototypes of the vacuum connection were used to test the form, fit and function in the early phases of design process (Gibson et al. 2010, 3).

5.2 Rapid prototyping

This Chapter describes the main aspects of rapid prototyping. All the technical details are not in the focus of this research report and thus left out in this context. There are multiple sources to find more comprehensive information about the technical aspects of rapid prototyping (e.g. Chua et al. 2010, Gibson et al. 2010 & Cooper 2001). As described earlier the commonly used term for technologies that produce objects layer-by-layer is 3D printing. In this research report rapid prototyping refers to layer-by-layer fabrication of physical *prototypes* directly from a computer-aided design (CAD).

5.2.1 Four main aspects of rapid prototyping

The development of rapid prototyping can be seen in four main areas (Chua et al. 2010). These are input, method, material and application. (Figure 20)

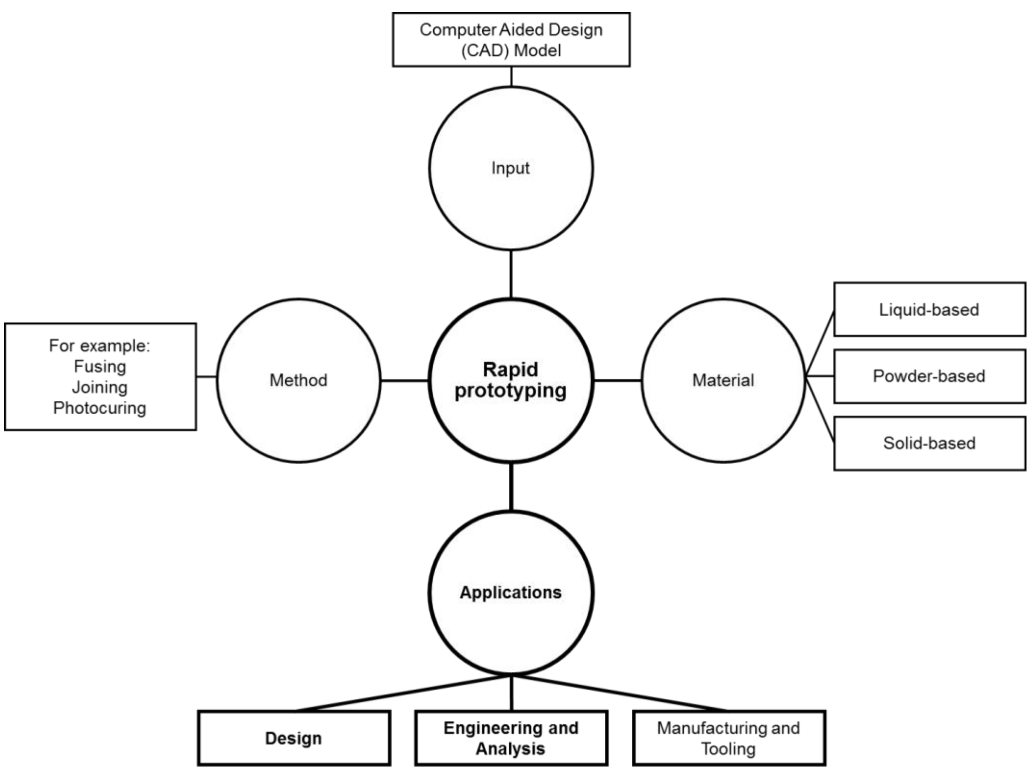

Figure 20 The four major aspects of rapid prototyping (Adapted from Chua et al. 2010, 12)

Input refers to the electronic information required to describe the physical object with 3D data. The computer model is created using CAD (computer-aided design) system(s). The starting point can be a physical model, but then reverse engineering is needed to turn the physical model's dimensions into 3D data on a computer. For example laser scanners can be used to capture the data points of the physical model and reconstruct it in a CAD system.

There are multiple different *methods* to create products or parts layer-by-layer. Different rapid prototyping technologies use different methods. These will be explained in more detail in the Chapter *5.2.4 Rapid prototyping technologies*.

There are multiple different *materials* that can be used with different methods. The initial state of material can be in liquid, powder or solid state. Examples of materials are paper, nylon, wax, resins, metals and ceramics.

Applications of rapid prototyping can be grouped to designing, engineering and analysis, and manufacturing and tooling. Instead of the term rapid prototyping, the term rapid tooling can be used when additive technologies are used to make tools, and the term rapid manufacturing can be used when additive technologies are used to manufacture end products.

This research report focuses on the *applications of rapid prototyping* and especially to the design, engineering and analysis applications (highlighted with bold text in figure 20).

5.2.2 Generic process of rapid prototyping

As stated before, rapid prototyping refers to layer-by-layer fabrication of physical prototypes directly from a computer-aided design (CAD). A more detailed, but still generic process of turning a virtual CAD model into a physical part or prototype is described here. (Figure 21)

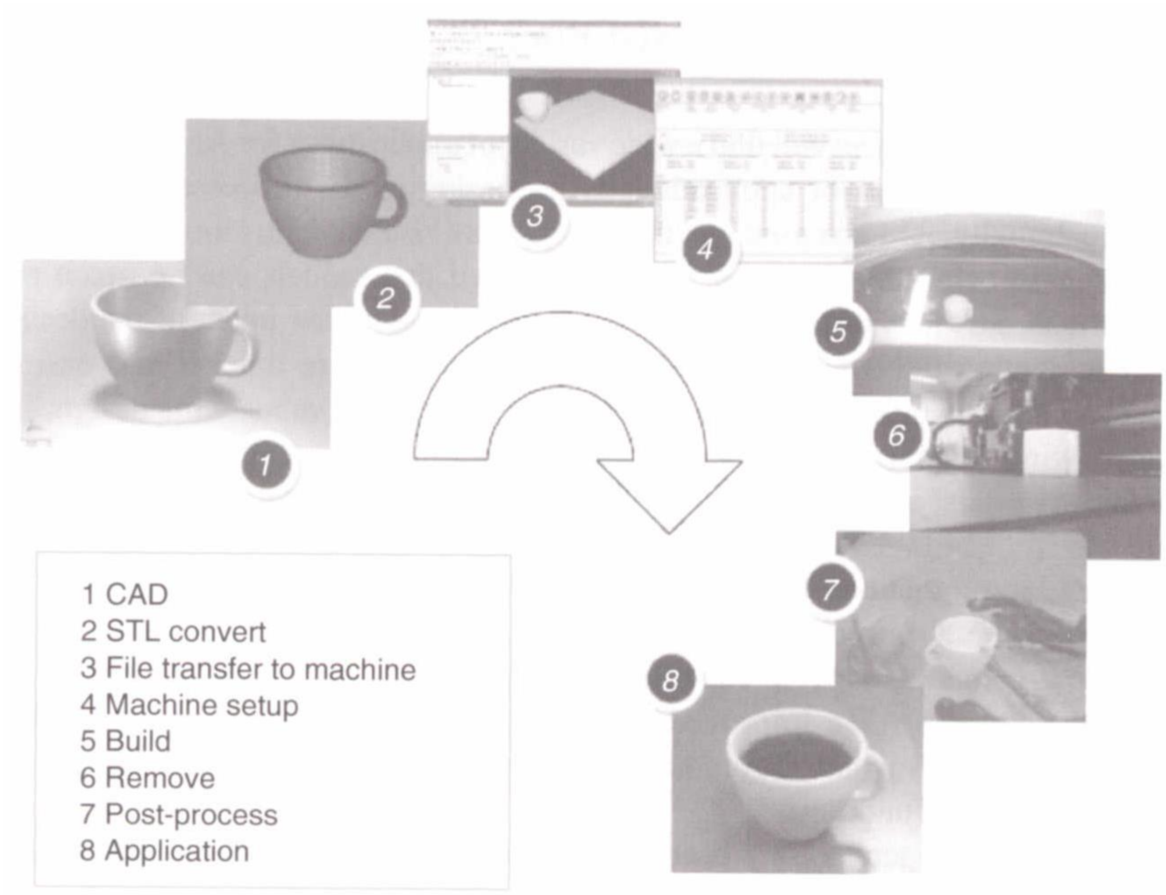

Figure 21 Generic process of CAD to part (Gibson et al. 2010, 3-6)

The rapid prototyping process must have a software model that fully describes the external geometry (phase 1 CAD). The CAD model is turned into a STL file format which describes the external closed surfaces of the original CAD model and forms the basis for the calculation of the slices to be printed (phase 2 STL convert). This STL format has become the standard file format that nearly every rapid prototyping machine accepts. Next the STL file is transferred to the rapid prototyping machine (phase 3 File transfer to machine). The rapid prototyping machine needs to be properly set up by defining settings like layer thickness, timings etc. (phase 4 Machine setup). The machine builds the part using an automated process. (phase 5 Build). Once the machine has completed the build, the part or prototype must be removed (phase 6 Remove). Parts or prototypes may require additional cleaning up before they are ready to use. Parts may be weak and they might have supporting features that must be removed. Additional treatments like priming, painting or infiltration of a strengthening substance might be needed. Thus parts or prototypes produced by rapid prototyping might need time consuming and careful, experienced manual manipulation. (phase 7 Post-process). After all these phases the part or prototype is ready to be used (phase 8 Application). (Gibson et al. 2010, 3-6)

5.2.3 Development of rapid prototyping: from labor intensive crafting to highly automated rapid prototyping

Prototyping has begun as early as humans started to develop tools. At the first phase prototypes were craft-based and extremely labor intensive. Computers and their applications of computer-aided design (CAD), computer-aided engineering (CAE) and computer-aided manufacturing (CAM) brought the second phase of prototyping. (Chua et al. 2010, 7-10) Improvements in the computing power and reduction in mass storage costs helped the computer-aided design modeling to process large amounts of data (Gibson et al. 2010, 17). In this phase soft or virtual prototyping could be performed, where prototypes are handled as computer models that can be modified, analyzed and tested virtually, as if they were physical prototypes. Rapid prototyping technologies have started the third phase where complex and difficult to produce models can be made fast and affordably. The first commercial rapid prototyping system was introduced 1988. (Chua et al. 2010, 7-10)

5.2.4 Rapid prototyping technologies

Rapid prototyping can be used as a general term to describe a technology which manufactures prototypes layer-by-layer. But actually there are multiple different rapid prototyping technologies that manufacture prototypes layer-by-layer using different methods that Chua et al. (2010) mention as one of the four major aspects of rapid prototyping (Figure 20). The process of manufacturing the part is referred here as the printing process. As mentioned before, all of the rapid prototyping technologies can be categorized into three groups according to which type of material they are using; liquid-based, solid-based or powder-based (Chua et al. 2010, 18). There are tens of different rapid prototyping technologies, but here four commonly used rapid prototyping technologies are described shortly. These same technologies can be used to also produce the end products or tools.

5.2.4.1 Stereolithography (SL)

Stereolithography was the first rapid prototyping process to reach the market in 1988. The stereolithography apparatus (SLA) has progressed through a long succession of models and advancements since its inception. SL is a liquid-based RP process, which builds parts by selectively curing, or hardening, a photosensitive resin with relatively low-powered laser. Stereolithography (SL) has the largest number of materials available for the process. The relatively large number of machines in the field and multiple vendors of photopolymer resins have fueled this growth. (Gornet 2006) During the printing process a UV laser traces out successive cross-sections of a three-dimensional object in a vat of liquid photosensitive polymer. As the laser traces the layer, the polymer solidifies and the excess areas are left as liquid. When a layer is completed, a leveling blade is moved across the surface to smooth it before depositing the next layer. The platform is lowered by a distance equal to the layer thickness and a subsequent layer is formed on top of the previously completed layers. Once complete, the part is elevated above the vat and drained. The excess polymer is swabbed or rinsed away from the surfaces. In many cases, a final cure is given by placing the part in a UV oven. After the final cure, supports are cut off the part and the surfaces can be polished, sanded or otherwise finished. (e.g. Chua et al. 2010, Gibson et al. 2010, Hopkinson & Dickens 2006, Cooper 2001) (Figure 22)

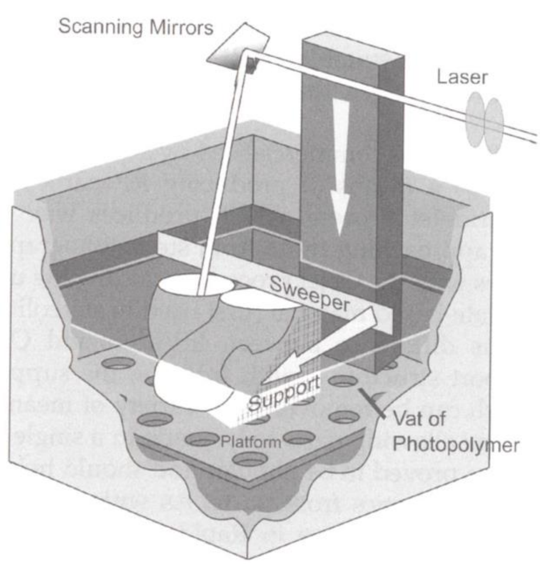

Figure 22 Stereolithography apparatus SLA (Hopkinson & Dickens 2006)

5.2.4.2 Selective laser sintering (SLS)

Selective laser sintering is a powder-based technology. It offers a wide variety of materials like polymers, metals and ceramics. Combing powders and layer additive manufacturing enables the possibility of functionally graded materials which will be described in more detail in the Chapter *5.4 Benefits of rapid prototyping*. The basic concept of selective laser sintering (SLS) is similar to that of SLA. It uses a moving laser beam to trace and selectively sinter powdered polymer and/or metal composite materials into successive cross-sections of a three-dimensional part. The parts are built upon a platform that adjusts in height equal to the thickness of the layer being built. Additional powder is deposited on top of each solidified layer and sintered. This powder is rolled onto the platform from a bin before building the layer. The powder is maintained at an elevated temperature so that it fuses easily upon exposure to the laser. Special support structures are not required because the excess powder in each layer acts as a support to the part being built. SLS also allows for a wide range of materials. (e.g. Chua et al. 2010, Gibson et al. 2010, Hopkinson & Dickens 2006, Cooper 2001) (Figure 23)

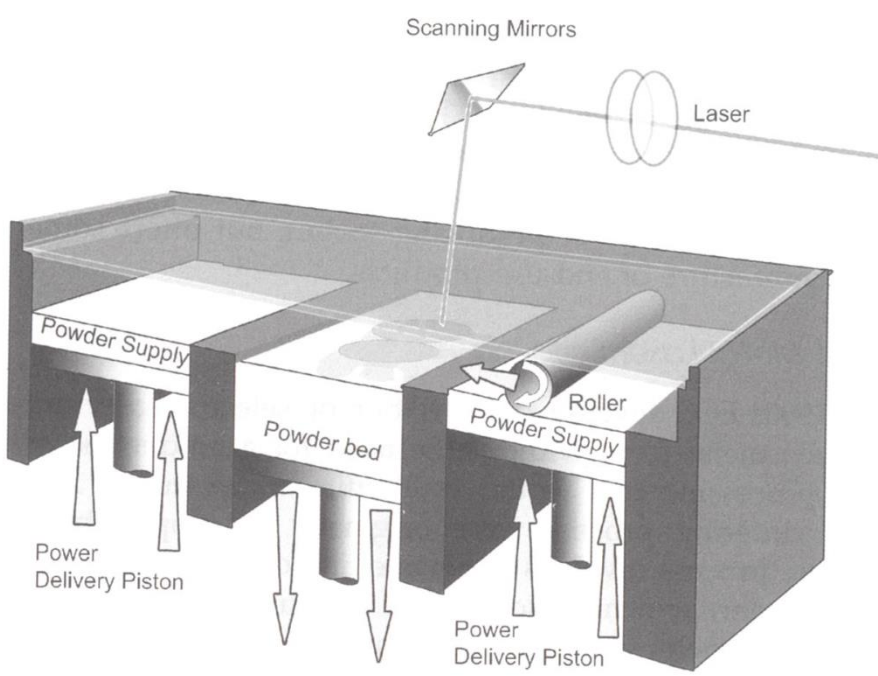

Figure 23 Selective laser sintering SLS (Hopkinson & Dickens 2006)

5.2.4.3 Fused deposit modeling (FDM)

Fused deposit modeling (FDM) is a solid-based technology. A plastic or wax material is extruded through a nozzle that traces the part's cross sectional geometry layer by layer. The build material is usually supplied in filament form, but some setups utilize plastic pellets fed from a hopper instead. The nozzle contains resistive heaters that keep the plastic at a temperature just above its melting point so that it flows easily through the nozzle and forms the layer. The plastic hardens immediately after flowing from the nozzle and bonds to the layer below. A separate support material feeder can be used to form supports if needed. Once a layer is built, the platform lowers, and the extrusion nozzle deposits another layer. A range of materials are available. (e.g. Chua et al. 2010, Gibson et al. 2010, Hopkinson & Dickens 2006, Cooper 2001) (Figure 24)

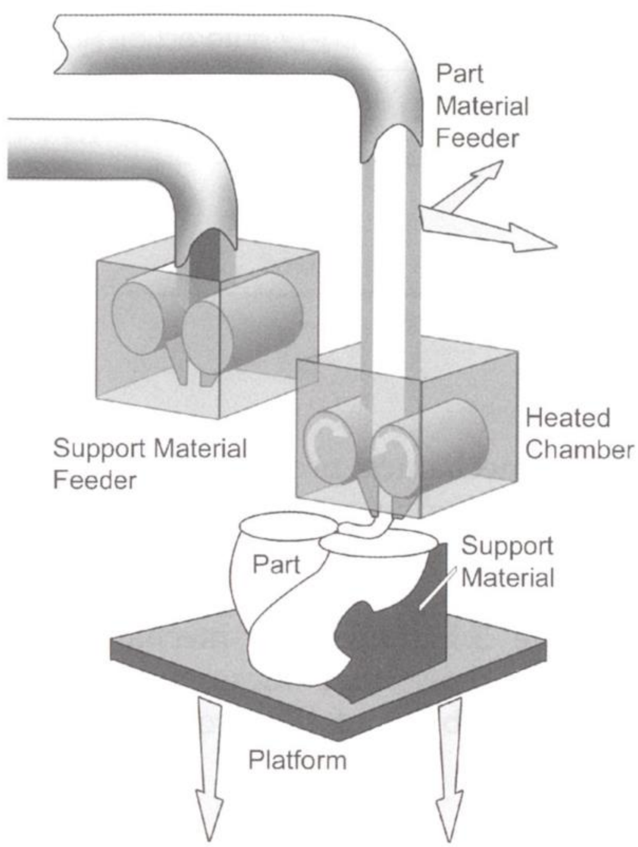

Figure 24 Fused deposit modeling FDM (Hopkinson & Dickens 2006)

5.2.4.4 3D Printing (3DP)

As mentioned before, 3D printing is a commonly used term to describe all additive technologies in the press. Here the original meaning of 3D printing as one of the rapid prototyping technologies is explained. 3D Printing (3DP) is also a powder-based technology like SLS. The 3D printing process begins with the powder supply being raised by a piston and a leveling roller distributing a thin layer of powder to the top of the build chamber. A multi-channel ink-jet print head then deposits a liquid adhesive to targeted regions of the powder bed. These regions of powder are bonded together by the adhesive and form one layer of the part. The remaining free standing powder supports the part during the build. After a layer is built, the build platform is lowered and a new layer of powder added, leveled, and the printing repeated. After the part is completed, the loose supporting powder can be brushed away and the part removed. 3D printed parts are typically infiltrated with a sealant to improve strength and surface finish. Material options are somewhat limited, but they are relatively inexpensive. (e.g. Chua et al. 2010, Gibson et al. 2010, Hopkinson & Dickens 2006, Cooper 2001) (Figure 25)

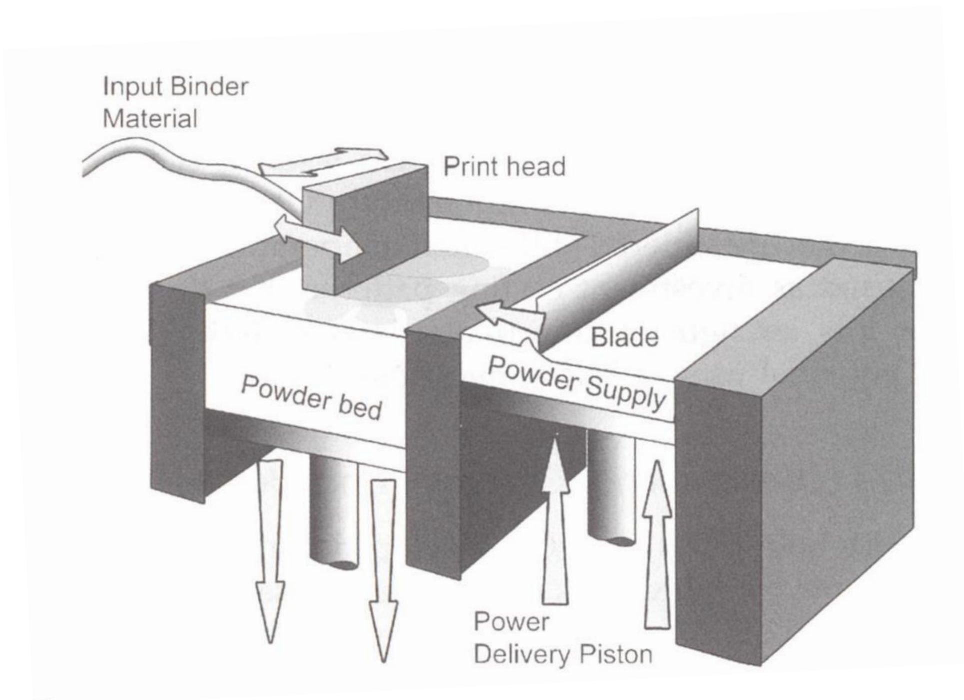

Figure 25 3D Printing 3DP (Hopkinson & Dickens 2006)

5.3 Design process and prototyping

Much time and effort is put into the design process of a product or a part, because the change-costs rise significantly when moving into large-scale or mass production. Costs accumulate already during the design process. (Figure 26) Changes in the later phases become increasingly expensive. Changes that occur late in the development process involve changing more product documentation and artifacts, and can have significant economic impact for example on manufacturing, distribution and packing. (Folkestad & Johnson 2002)

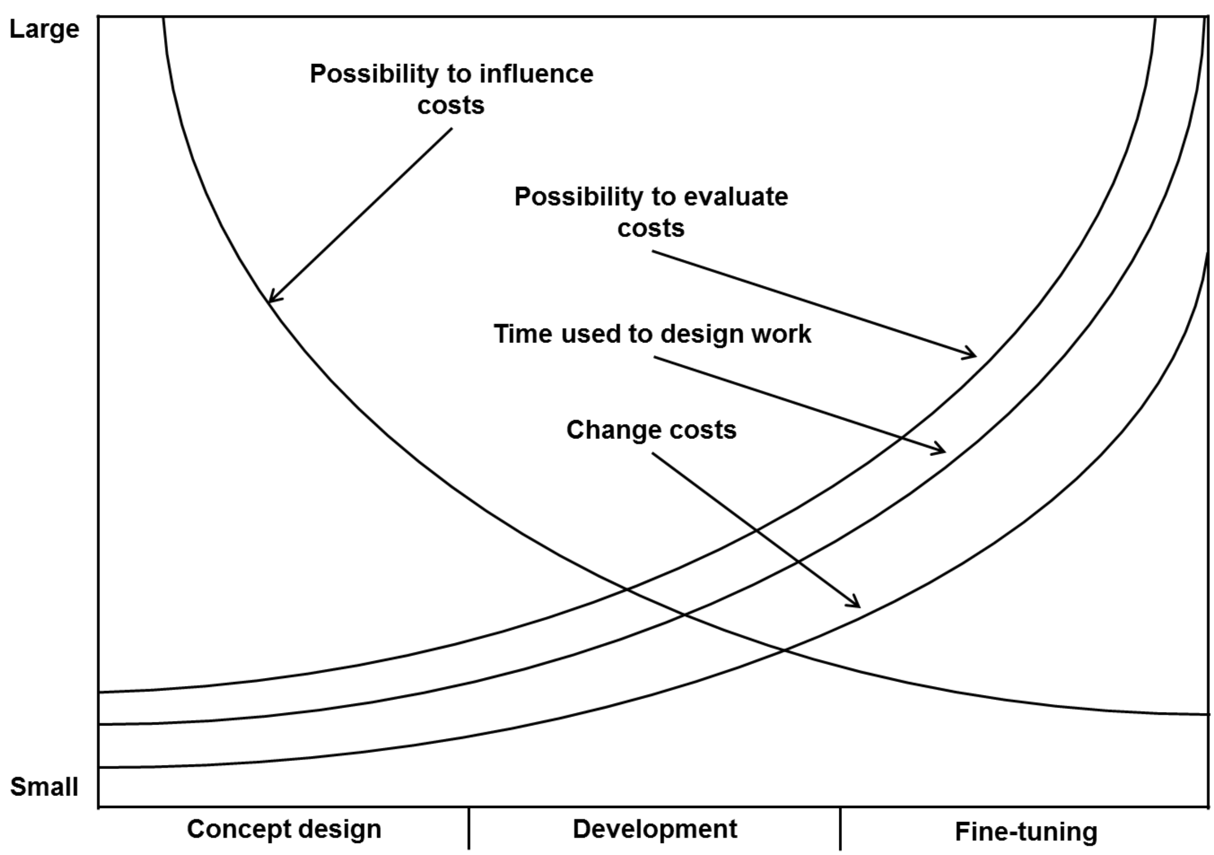

Figure 26 Cost formation during the design process (Sederholm, Simons & Syrjälä 1993, 7)

5.3.1 Description of design process

Here the description of a typical design process when rapid prototyping is not used is presented. Techniques for approaching a design process may vary from business to business, but a general path for a mass-production item is described in figure 27.

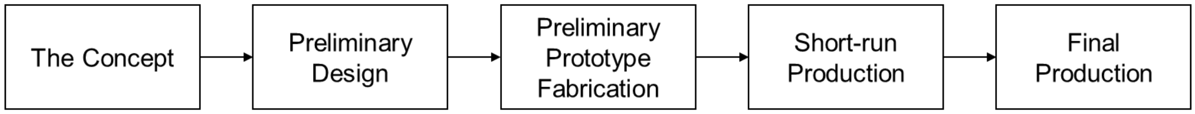

Figure 27 Typical design process (Adapted from Cooper 2001, 3-4)

Any new product or improvement of an old product starts with a *concept* or idea. A *preliminary design* is made from the concept. It can be done in any form (e.g. a sketch on paper or a CAD model). The design can go through much iteration during this phase as the designer determines the feasibility of the product and several parties can be involved in developing the design (co-workers, management etc.). Also preliminary checks can be performed with for example computer analysis. From the preliminary design a *preliminary prototype* is fabricated to check the design. Sometimes a *short-run production* sequence may be necessary to further prove a part before entering the final production. Anywhere from ten to a few hundred parts may be manufactured and distributed for testing, verification, consumer satisfaction etc. In the *final production* parts or products are typically either machined, injection molded, or cast in large numbers. (Cooper 2001, 3-4)

When rapid prototyping technologies are not used, the preliminary design is usually kept as a two dimensional drawing or a CAD design on a computer. If a preliminary prototype is fabricated to a physical object, it is usually done by hand working or machining which can both be time consuming and expensive. This is why not many physical prototypes are made. (Cooper 2001, 3-4)

The design process of vacuum connection, if rapid prototyping would not have been used

The chief design engineer was asked to describe how the design process and prototyping of the vacuum connection had been progressed, if rapid prototyping would not have been used. The following findings were made according to the answers.

Prototypes of the vacuum connection would probably have been done even without the use of rapid prototyping, but the methods would have been workshop based.

"Probably the first prototypes would have been done with really traditional methods like welding or casting"

Changes to the design of the vacuum connection would have been done a lot more in computer aided design systems and the physical prototypes would have been done later in the process. This would have probably led to a lower quality design.

"--- the development work would have been probably continued for a year longer with computer aided design (CAD) before we would have felt that now we are so ready that we can start to make that pre-series."

"The concept would have been developed with the limitations of 3D modeling (CAD), which would have created many restrictions to the design of the part."

Eventually the vacuum connection would probably not have got the same design, as if rapid prototyping was used. Especially the flow properties would have been harder to optimize without rapid prototyping.

"For sure the optimal design for the flow would have been secondary and the focus would have been on other functional features than optimal flow."

On the other hand the design for manufacture (DFM) philosophy, where manufacturing is considered early in the design process, would have probably been concerned earlier in the process.

"We would have done the 3D model and after that contacted supplier and waited, that we would get proposal from the supplier, that this is the kind of part that they can manufacture, and this is what you will get."

Based on the chief engineer's description, figure 28 is a simplified description of how the design process would have been done, if rapid prototyping was not used.

Figure 28 Description of the design process of vacuum connection, if rapid prototyping was not used

This description is very similar with the typical design process described in figure 28. The phases are the same, but the interviewed chief engineer stressed the long preliminary design time needed in CAD systems, when rapid prototyping is not used to make prototypes early in the design process.

5.3.2 Rapid prototyping as part of the design process

Rapid prototyping is used as a communication and inspection tool in the procedure of product development and realization of rapid feedback of design information. Companies using rapid prototyping can shift the number of product design changes from the late phase of development to the early phase of development and thus save a lot of costs and time (Folkestad & Johnson 2002). Detlef, Chua & Zhaohui (1999) suggest that a product development system which is dynamic, controllable and simultaneous should be realized under the development system described in figure 29.

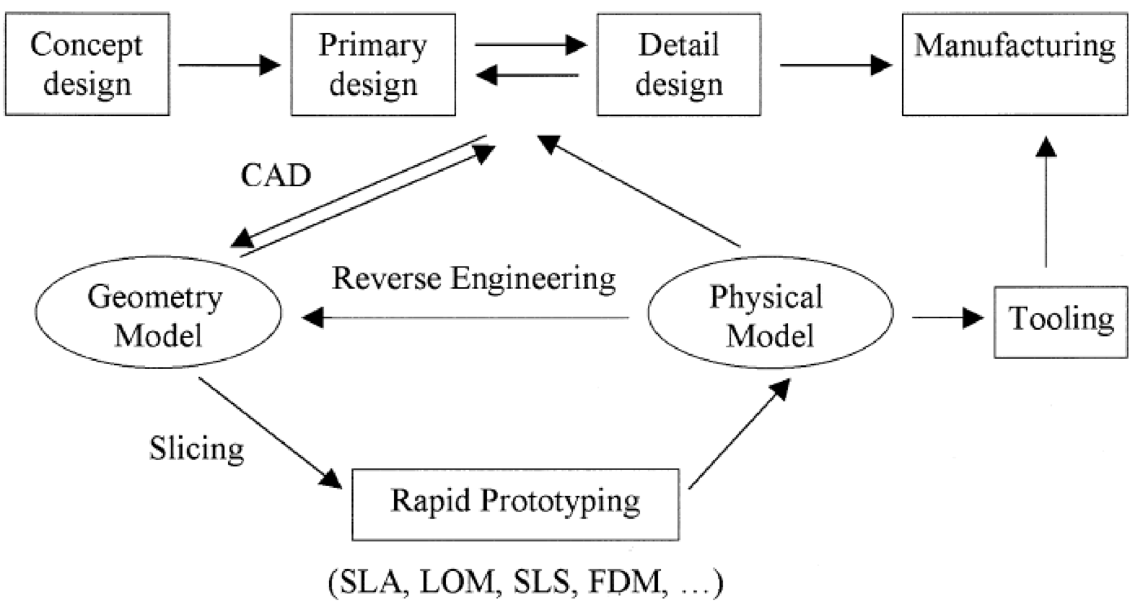

Figure 29 Product development system based on RP (Detlef et al. 1999)

When compared to the previously described typical design process (Figure 27) the clear distinction is the more iterative process with many possible physical prototypes.

Design process of vacuum connection when rapid prototyping was used

As can be seen from the written description of the case design process in Chapter *4.4 Description of the design process and prototyping of vacuum connection* and in the summary of the design process in appendix 3, five different generations of prototypes were made. Different kinds of tests were done with each of the prototypes, which gave feedback for the chief engineer. Thus the process can be described in a simplified manner as figure 30.

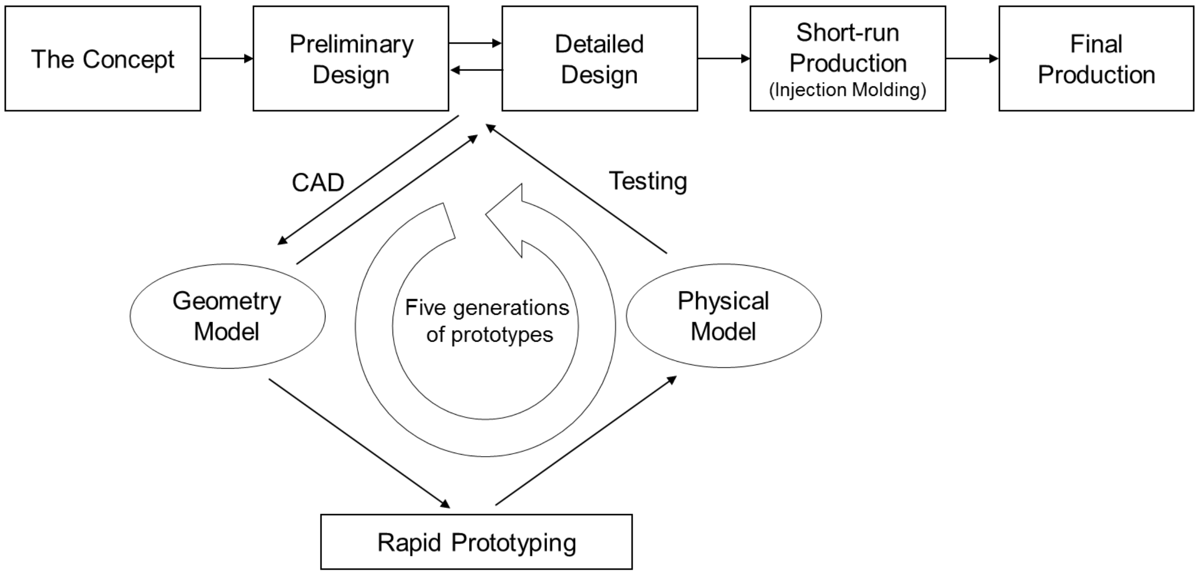

Figure 30 Description of the design process of vacuum connection

This design process in figure 30 really is very similar to one which Detlef et al. (1999) uses to describe the product development system based on rapid prototyping (Figure 29).

5.4 Benefits of rapid prototyping

In this Chapter the benefits of rapid prototyping are first listed according to the empirical findings from the primary and the secondary data. Then they are summarized. These benefits are compared against other methods and technologies used to produce prototypes like injection molding. One of the theoretical propositions for which this research was based on is that rapid prototyping needs to have some benefits, when compared against other methods and technologies used to produce prototypes, for it to be a potentially disruptive technology. Thus the aim is not to provide a comprehensive list of benefits, but to give a general understanding of why rapid prototyping could be a potentially disruptive technology.

5.4.1 List of benefits

Design freedom and complexity of geometry without extra cost

Rapid prototyping enables the creation of products or parts with almost any geometry. With rapid prototyping the bottleneck might be in many cases the design, while making them is the easy part. (Hopkinson et al. 2006, 2) In the conventional manufacturing of prototypes, there is a direct link between the complexity of the part and its cost. With rapid prototyping the complexity of the part is not linked to the cost (Hague 2006, 5).

This affects the way products or parts can and should be designed. Hague (2006, 7) describes conventional design for manufacture (DFM) and design for assembly (DFA). *Design for manufacture* is a philosophy or mind-set in which manufacturing input is used at the earliest stages of design in order to design parts and products that can be produced more easily and more economically. *Design for assembly* means that reductions in manufacturing cost and improvements in the ease of assembly are being pursued in design. This can be achieved for example by reducing parts count, reducing handling time and ease of insertion. These philosophies mean that already at the design phase of the first prototypes possible manufacturing restrictions are taken into consideration. With rapid prototyping there are far less of DFM and DFA restrictions or they can be totally forgotten as long as the final product is manufactured with a suitable technology like additive manufacturing.

When building parts in an additive manner one always has access to the inside of the part or product. This enables the manufacturing of operational mechanisms that could not be manufactured by any other technology. As the additive manufacturing technologies evolve, the production of 3D integrated electronics can become possible, and this can have a radical impact on the possibilities of electronic products. (Gibson et al. 2010, 292 – 294)

It was raised many times in the interviews, that the vacuum connection was more freely designed than before, because almost any design could be produced using rapid prototyping. Especially the optimal design for liquid flow was looked for, because a lot of liquid moved through the vacuum connection. The vacuum connection was one part of the flow process where the speed and efficiency of the whole filtration process could be optimized.

"We were able to start making the prototypes purely based on the optimal design needed for the liquid flow and we didn't need to consider manufacturing technology at the beginning of development…we didn't need to consider the restrictions."

As described earlier, the conventional DFM philosophy was not needed to take into consideration, as almost any design could be produced with rapid prototyping. DFA was still considered throughout the process as the vacuum connection was assembled to the filter disc, which design was not going to be changed.

"--- we have not locked our thinking to the available manufacturing technologies and techniques in the early phases of the project."

Both of the quotes above were given at the first interview. Thus they were given before the problems with the suitability of the design for injection molding were noticed. The challenge of manufacturing according to the designed prototype will be described later in this research report.

Simpler designs

Part count can be reduced by combining features into single-piece parts that were previously made from several pieces, because of, for example, poor tool accessibility or the need to minimize machining and waste. Fewer parts reduce time spent on analysis, selecting fasteners, detailing screw holes and assembly drawings. (Chua et al. 2010, 15) It is often possible to design the consolidated parts to perform better than assemblies (Gibson et al, 2010, 296).

The complexity of the old design of the vacuum connection was one of the main reasons the design process for the new vacuum connection was started. Simpler design with fewer parts was looked for and this result was also achieved in the design process.

"This (new design) is clearly simpler. Mechanically the old version had sixteen components and this has eight components. Also the assembly is clearly simpler --- This has also significantly better quality."

Hierarchical Structures

With additive technologies hierarchical structures can be made. The basic idea of hierarchical structures is that features at one size scale can have smaller features added to them, and each of those smaller features can have smaller features added etc. One example is cellular materials (materials with voids) like for example honeycombs and lattice structures. Materials can be put only where it is needed for a specific application and thus, for example, high strength with relatively low mass can be achieved. These materials can also provide good energy absorption and good thermal and acoustic insulation properties as well. (Gibson et al. 2010, 297) The vacuum connection did not have any hierarchical structures in it.

Material Combinations

The possibility to mix and grade materials can be available as additive technologies evolve. There are already printers that can do this. For example Objet's digital materials are made up of two Objet materials. The two materials are combined in specific concentrations and structures, to provide the desired mechanical properties and to resemble the product's target materials. (Source: Objet website <http://objet.com/3d-printing-materials/digital-materials>) This enables the materials with certain needed properties to be deposited where they are needed. (Hague et al. 2003)

Examples of these kinds of materials are functionally graded materials (FGMs). Functionally graded materials are a form of composite where the properties change gradually with position. (Figure 31) They can be used to meet specific needs in the different locations of the same part. For example, a bone implant can be formed by a strong and tough material in the core with graded bone tissue compatible material to the surface and low friction material in the joints. In addition to medical applications of FGMs, they can be used for example in aerospace and sporting goods. (Erasenthiran & Beal 2006)

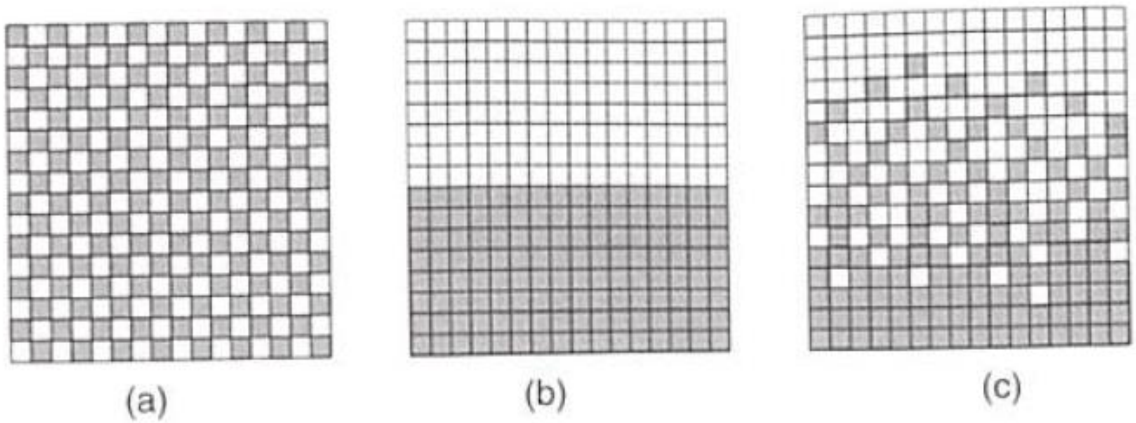

Figure 31 Illustration of (a) homogeneous, (b) coated or joint type and (c) FGM (Erasenthiran & Beal 2006)

The vacuum connection was made by using a single material and thus the possible benefits of material combinations were not considered.

Time saving

Rapid prototyping can have a significant impact on time required to make the prototype. This advantage becomes especially apparent with small sized complex structures with for example, internal cavities. (Evans & Campbell 2003) Small series production can be made early in the design process to do function testing and get the proof-of-concept. A lot of costs and time are saved as changes from the late phase of development can be moved to the early phase of development. (e.g. Chua et al. 2010, Folkestad & Johnson 2002) (Figure 32)

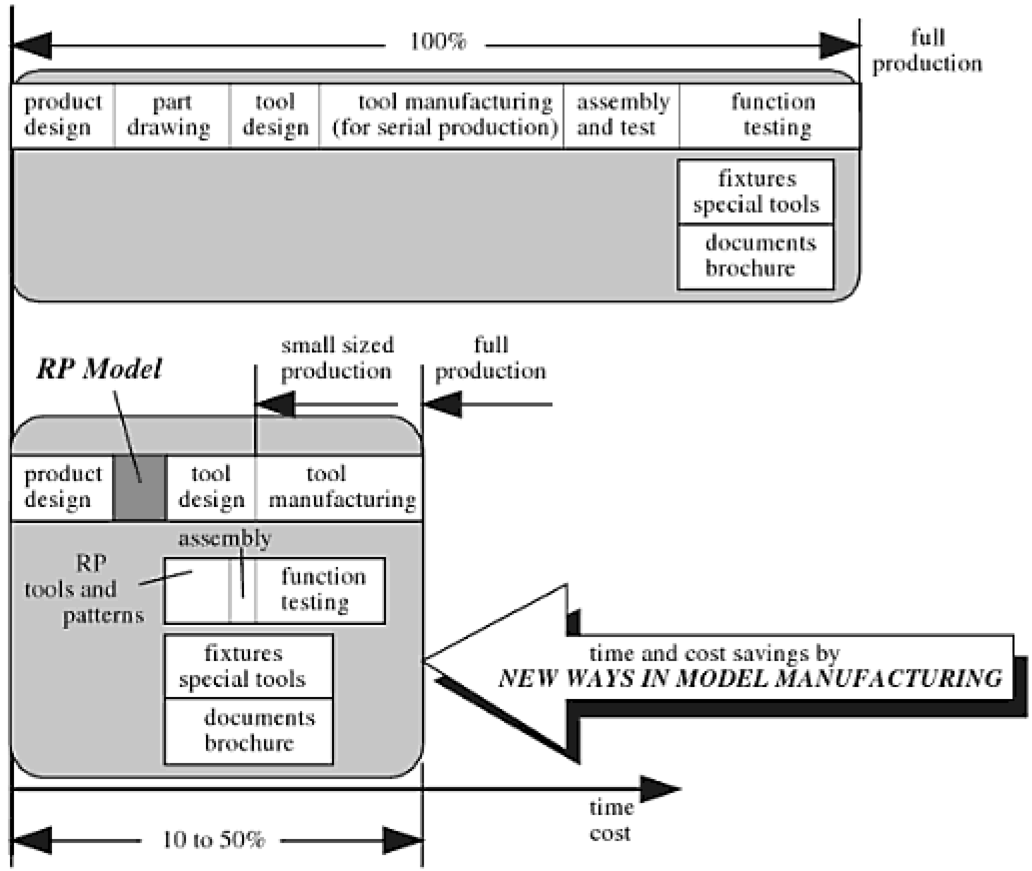

Figure 32 Results of the integration of RP technologies (Chua et al. 2010, 15)

Prototypes of the vacuum connection were done in a fast phase with rapid prototyping. Thus the time from a new design to the actual testing of it was shortened. This reduced the time needed to complete the new design as the feedback of the design was received in a short period. Overall the time needed for the design process got shorter.

"With the use of rapid prototyping you can get the part to your hands with very short notice and you get to test it in practice. This way the needed design time gets shorter. I am not necessary saying that planning hours would be lower, but the designing work progresses much faster and then overall time needed for the design process gets shorter."

As the chief engineer explains, it takes time and man-hours to make the CAD designs on computer whether prototypes are used or not, but with rapid prototyping many prototypes can be made fast and tested which gives feedback to the design.

Less waste

In many of the used rapid prototyping technologies, like stereolithography (SL) and selective laser sintering (SLS), the excess material can be collected and re-used. Only the material that is needed to produce the product or a part is used. Although, for example SLS powder materials have restrictions on the potential re-use of the powder (Hopkinson 2006).

Material savings were not in the interest of Outotec people involved as rapid prototyping was bought as a service from an outside supplier. Thus possible material savings gained in the production were savings to the supplier.

Lower cost per product with small series

One clear distinction between rapid prototyping and other manufacturing technologies is the different cost structure. Rapid prototyping has a totally different cost structure than, for example, techniques like injection molding. Hopkinson & Dickens (2003) have done a cost analysis where manufacturing costs per part has been compared by injection molding, stereolithography (SL), fused deposit modeling (FDM) and selective laser sintering (SLS). As can be seen in figure 33, the economies-of-scale rationale of serial or mass production does not apply to rapid prototyping. This is why one of the biggest benefits of rapid prototyping is the design freedom and complexity of geometry *without extra cost*.

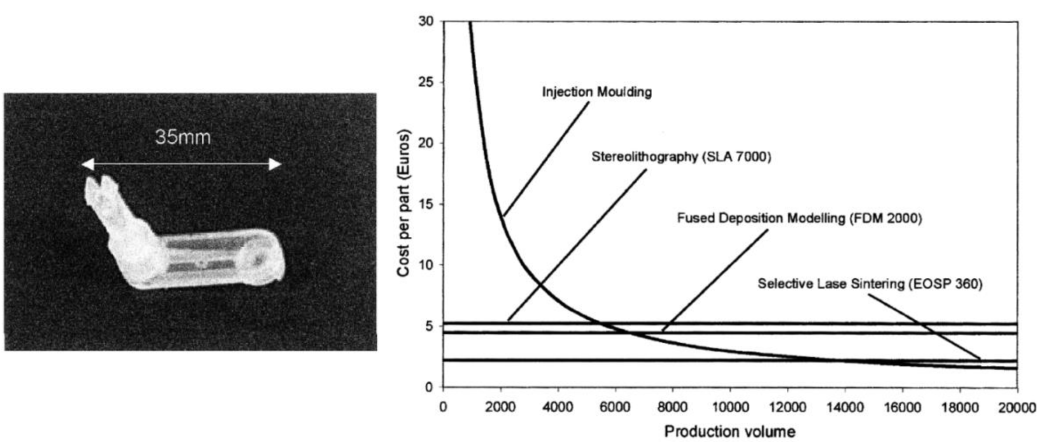

Figure 33 35mm lever part with the graph of cost comparison for the lever by different processes (Hopkinson & Dickens 2003)

As part size grows, the cut-off volume, where rapid prototyping is cheaper per part, gets smaller. This means that rapid prototyping processes are more suitable for the production of smaller parts (Hopkinson & Dickens 2003). Similar results and the same kind of cost structure have also been achieved with metal parts, when comparing the traditional high-pressure die-casting and the direct metal laser sintering which is one of the additive technologies. (Atzeni & Salmi 2012)

The case example of the vacuum connection also showed, that rapid prototyping provides lower cost per product with small series and small enough part size. This was also one of the main reasons rapid prototyping was taken into use in the case design process of the vacuum connection.

"You could roughly say that with the price of one printed prototype a designer could have done couple of hours of CAD designing. So it (rapid prototyping) is definitely worth using."

"The prototyping costs (when used other technologies) would have probably been many times larger compared to the rapid prototyping."

The decision to move to injection molding based manufacturing with the larger series was based on two things, the lower cost per part being the other one and the better material as the other. This also supports the earlier findings about the cost structure differences (Hopkinson & Dickens 2003).

"As we start to make tens, or I would guess that pre-series is some hundreds of pieces, the costs of rapid prototyping are not competitive any more. And as a second advantage we get the material information about the material that is going to be eventually used."

Reduced risk

With rapid prototyping the product's final design can be confirmed early in the process. Prototypes can also be tested in real life situation throughout the process. These advantages help to protect against the expensive change costs at the end of design phase (Figure 26) (Sederholm, Simons & Syrjälä 1993).

The rise of the change costs as the design process moves forward was also recognized during the case design process of the vacuum connection. Prototypes were used for testing in many different phases. First form and fit of the part were tested. The correct fit to the filtration disc and correct form for the optimized flow of liquid were first looked after. After these were set, the function was tested in a real Outotec Larox CC machine to make sure everything worked as expected. With rapid prototyping the testing could be started early in the process which also made it possible to make the needed changes early in the process.

"It (rapid prototyping) definitely speeds up the product development project and reduces the financial risks and thus the overall costs. We don't need to make expensive mistakes. Product can be designed to the quite detailed ready design with rapid prototyping."

It was also noted that the real practical tests can give more reliable results than tests done virtually. This also reduces the risks of making decisions on false test results. When the flow tests were first made virtually in a Computerized Fluid Dynamics (CFD) program, the results suggested approximately twice better flow through the vacuum connection. With the real produced prototype the results were only approximately ten percent better compared to the old design. The chief engineer thought that the vacuum connection was not the bottleneck in either case, but the flow features of the filtration disc was crucial. But now with the new design of the vacuum connection, the benefits of possible better filtration discs in the future can be fully achieved as vacuum connection will not be the bottle neck.

Better visualization of the prototype

Prototypes in general enable better visualization than the 3D model in CAD program that is viewed from a computer screen. Rapid prototyping is not the only technology to make prototypes and thus the better visualization of the prototype cannot be distinctively a benefit of rapid prototyping. But in the case design process, rapid prototyping enabled the manufacturing of high precision prototypes, which would not have been done at least in such an early phase of the design process, if rapid prototyping was not used. Thus rapid prototyping can be seen as enabling technology for well visualized prototypes.

"With rapid prototyping we could visualize the part and its functionality in practice much better."

"As you take those two parts together, an experienced engineer can see right away is the looseness between the parts correct or should the tolerances be changed. In that kind of a practical measurements' definition this (rapid prototyping) has been absolutely excellent help."

5.4.2 Summary of the benefits of rapid prototyping

Benefits of rapid prorotyping	Case (Primary data)	Previous literature and research (Secondary data)
Design freedom and complexity of geometry without extra cost	X	X
Simpler Design	X	X
Hierachical structures		X
Material combinations		X
Time savings	X	X
Less waste		X
Lower cost per product with small series	X	X
Reduced risk	X	X
Better visualization of the prototype (not a distinctive benefit of rapid prototyping)	X	

Table 1 Summary of the benefits of rapid prototyping

Table 1 provides a summary of the benefits of rapid prototyping based on the primary and secondary data. As mentioned already before, the aim is not to provide a comprehensive list of benefits, but to give a general understanding of why rapid prototyping could be a potentially disruptive technology. It can be seen that in the case design process of the vacuum connection, the possibilities of hierarchical structures and material combinations were not utilized. These might be benefits that could be considered in the future design processes. Waste savings were not identified by the chief engineer in the interviews. This was probably because they were not visible for him as the rapid prototyping was ordered from an outside supplier. The chief engineer expressed many times how prototypes made with rapid prototyping enabled better visualization of the prototype. As described, this cannot be distinctively a benefit of rapid prototyping, but rather a benefit of using prototypes in general. But it has been shown that rapid prototyping enables the use of prototypes earlier and more often in the design process, and thus this benefit could be highlighted more also in the literature of rapid prototyping.

Many of the benefits described above ultimately reduce the time needed for the design process and also drive cost savings. As the rapid prototyping technologies evolve, these benefits become even greater. This can also be seen when looking at the historical development of design processes. The development of rapid prototyping technologies and thus the increase in the benefits has resulted in shortened project times even though the relative prototype complexity has increased (Figure 34).

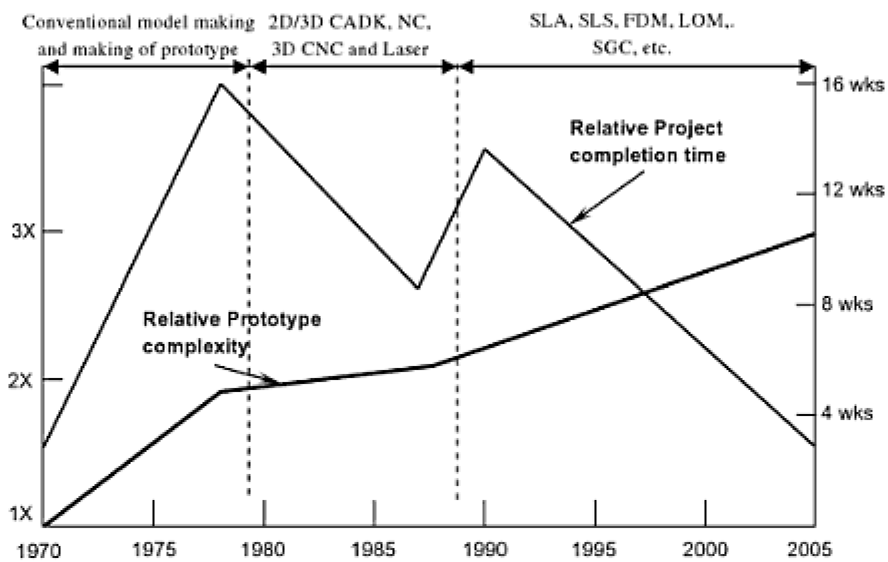

Figure 34 Project time and product complexity in 25 years time frame (Chua et al. 2010, 14)

5.5 Limitations of rapid prototyping

There are also limitations in the use of rapid prototyping. The materials and properties of rapid prototyped parts often fail to match their molded or machined counterparts. Even though the current limitation in material properties lies probably in the fact that they are not known sufficiently rather than they are not good enough. Also the accuracy, detail and surface finish are all aspects of rapid prototyping that are a disadvantage when compared to other manufacturing technologies. (Hopkinson & Dickens 2003) The price per kilogram of materials for rapid prototyping is also far higher than those for conventional manufacturing processes. (Hopkinson 2006)

5.5.1 Limitations of rapid prototyping identified in the case

For the Outotec people involved in the design process of the vacuum connection, this was the first time rapid prototyping was used to make prototypes. In this sense they were also in a good position to evaluate the challenges that a move to rapid prototyping can bring.

Challenges when moving from rapid prototyping to another manufacturing technology

The search for a possible supplier of injection molded parts started after the third generation prototypes. At this point the results from the tests were good and the team was quite satisfied with the new design. It was found out, that none of the contacted suppliers of injection molding could produce the vacuum connection, as it was designed in the third generation prototype. Thus the focus in the design moved more to the DFM and some changes to the design needed to be done at a cost of losing some of the flow properties. The changes were made in co-operation with one of the suppliers of injection molding.

"--- we have now discussed with one supplier of injection molding about the manufacturing of first small series production and they did not like the design of the vacuum connection. They cannot manufacture the design by injection molding, or at least not in a simple way."

"I don't like the idea that after getting this kind of design done it would be changed because of the manufacturing technology of one supplier."

The design was first made without considering the DFM philosophy, because with rapid prototyping almost any design was able to be manufactured. Thus the needed changes were not welcomed at first, but eventually the needed changes were quite modest and no bigger problems were encountered. Probably in the future design processes the suppliers will be contacted earlier.

" --- maybe we would contact the supplier (of injection molding) earlier and get the comments of the manufacturing technique (if this design process could be started again from the beginning)."

Material limitations

Different rapid prototyping technologies and materials were considered when a new supplier for the printed third generation prototype was looked for. After discussing with one rapid prototyping supplier, ten different possible materials with samples were selected. From these ten materials, three were selected to be tested for acid resistance. After these tests, two of the three tested materials were found suitable and one of them selected as the material for the produced prototypes. The selected material was infiltrated for better water and air tightness needed in testing. After infiltration the prototypes had the needed properties to perform real life testing in the Outotec Larox CC machine, but the material was not relied upon to be held in the machine more than a couple of months.

"Rapid prototyping materials cannot be used for every purpose. They have certain heat resistance limits and chemical limitations, which need to be taken into consideration in real life and that is why you cannot necessary test them in real situations."

It was also noted that infiltration may have shrunk the measures of the part just a bit and made the tolerances between different parts a bit loose.

" --- apparently something happens to the measures of the part when it is infiltrated, as the tolerances are clearly more lose in these (infiltrated parts) than in the first ones (not infiltrated)"

5.5.2 Summary of limitations of rapid prototyping

Limitations of rapid prorotyping	Case (Primary data)	Previous literature and research (Secondary data)
Material limitations	X	X
Accuracy, detail and surface finish		X
Challenges when moving form rapid prototyping to another manufacturing technology	X	

Table 2 Summary of the limitations of rapid prototyping

A summary of the limitations of rapid prototyping is described in table 2. Material limitations of rapid prototyping were identified in the case and in the previous literature and research. Hopkinson & Dickens (2003) suggest that the current limitations in rapid prototyping material properties lie probably in the fact that they are not known sufficiently rather than they are not good enough. This could also be seen in the case as material selection for rapid prototyping took time in the design process and a separate visit to the rapid prototyping supplier was arranged to get an understanding of different materials available. Three materials were also sent to acid testing to make sure they were acid resistant enough. This suggests that more information about the different rapid prototyping materials is probably needed in the future.

SLS was selected as a rapid prototyping technology in the case. This technology provided sufficient accuracy, detail and surface finish for the vacuum connection prototypes. Different purposes and applications of prototypes define the needed accuracy, detail and surface finish. And different rapid prototyping technologies and machines can provide different qualities of the part. Thus sufficient accuracy, detail and surface finish probably differ case by case.

In the case, challenges were noticed when the design of the third prototype needed to be manufactured by injection molding. As rapid prototyping makes it possible to produce almost any geometry, the DFM and DFA principles can be easily forgotten. This is not a challenge or a problem, if rapid manufacturing technologies are used to produce the end products or parts. But like in the case, the manufacturing technology of larger series or mass production is still often other technologies like injection molding. Thus DFM and DFA need still to be considered.

Generally the context where rapid prototyping is used needs be considered when looking at the benefits and limitations of rapid prototyping. As for example Hopkinson & Dickens (2003) have noted, the rapid prototyping processes are more suitable for the production of smaller parts. Also, available materials and their properties may constrain the suitability of rapid prototyping for certain applications. All the benefits can be utilized, if the same additive technologies are and can be used to produce the final products. Otherwise the manufacturing technology can limit the possible designs as happened in the case.

6. Discussion

6.1 Rapid prototyping as a potentially disruptive technology

As described in the summary of the disruptive technologies, many models describing the development of disruptive technologies acknowledge that the performance metrics are relevant in defining a disruptive technology. They also suggest that these metrics are defined by the customers and their needs. (c.f. Christensen & Raynor 2003, Moore 1991) Empirical findings of this research show that rapid prototyping seems to have benefits that customers value. These benefits are still very dependent on the context. It was noted for example that when the size of the prototype grows, the cost benefit for rapid prototyping per part decreases (c.f. Hopkinson & Dickens 2003). Also, available materials and their properties may constrain the suitability of rapid prototyping for certain applications.

Rapid prototyping seems to evolve as low-end disruption as Christensen (1997) has defined it. Rapid prototyping had and still has many times worse product performance than other technologies and methods like injection molding. Limitations in materials, accuracy, details and surface quality are examples of the worse product performance. But the value proposition of rapid prototyping is different than other technologies. Even though there are limitations in the use of rapid prototyping there are also several benefits as described in this research report. A different cost structure and the possibilities of geometry freedom are valuable for certain customer groups. Rapid prototyping has also been able to compete with non-consumption and create new-market disruptions like Christensen & Raynor (2003) describe them. The maker movement is one example of this kind of new-market disruption and it will be discussed next.

6.1.1 Maker movement and low cost 3D printers may bring product innovations outside the R&D departments of companies

Because rapid prototyping enables individuals to produce any kind of design cheaply, it has opened a possibility for new customer segments in prototyping. Would-be entrepreneurs and inventors need no longer the help of large companies to manufacture their ideas. Anderson (2012) calls this group of people as "makers". Together they form a network of "maker movement" that industrializes their do-it-yourself (DIY) spirit. Just as the Web democratized innovation in bits, a new class of rapid prototyping is democratizing innovation in atoms. Anderson emphasizes that "the biggest transformation is not in the way things are done, but in *who's doing it*". Rapid prototyping technologies have lowered the barriers to entry for physical designing. CAD programs have become easier to use and basic programs are free of charge. The number of low cost 3D printers are rising constantly which will enable all the consumers to own their own 3D printer which they can use to make prototypes. (Gartner 2011) Also, service providers like Shapeways can be used to make professional quality prototypes with more expensive rapid prototyping machines with still a relatively low cost per prototype (Source: Shapeways website <http://www.shapeways.com>). All these changes can potentially mean that more product innovations will be done outside established companies R&D departments, because anyone with a product idea can have access to affordable tools to realize it.

The maker movement and low cost 3D printers have brought prototyping to new customers who previously could not afford to do it. In this sense rapid prototyping has caused new-market disruptions as Christensen & Raynor (2003) have defined it. Prototypes made with rapid prototyping technologies are so much more affordable to own and simpler to use that they enable a whole new population of people to begin owning and using the product, and to do so in a more convenient setting.

6.1.2 Rapid prototyping may break the tight interrelationship of product and process innovation in prototyping

In the fluid phase of the product and process innovation model (Utterback 1994, 82), the processes used to produce the new innovative product are usually “crude, inefficient and based on mixture of skilled labor and general-purpose machinery and tools”. Labor intensive workshop-based fabrication techniques may need to be used, because no specialized tools, machines or dedicated craft conditions exist. This reflects the situation of prototype making without the use of rapid prototyping technologies (Cooper 2001). In the model of product and process innovation, the process innovation grows and the product innovation decreases as dominant designs start to take place and process innovations increase to make the production as efficient as possible.

Utterback describes the tight interrelationship of product and process innovation as follows:

> *“Changes in product design seem initially to shape the course taken in the development of the production process. Later the early choices made in process technology may constrain further developments in the product. When both product and process designs are highly elaborated, they may become so intertwined and codependent that neither can change without deeply influencing the other.” (Utterback 1994, 76)*

Before the rapid prototyping technologies were used, the preliminary prototype was fabricated to a physical object usually by hand working or machining which both can be time consuming and expensive (Cooper 2001). Rapid prototyping has changed this “crude and inefficient” process at the beginning of some product development processes and breaks the tight interrelationship between product and process innovation, because the product innovation’s designs, no matter how complicated, can be directly manufactured with rapid prototyping technologies. No tooling, machining or separate process innovations are needed in between. Thus the gap between product innovation and process innovation needed to produce the product can become smaller and the dynamics can ultimately be the same for both. (Figure 35)

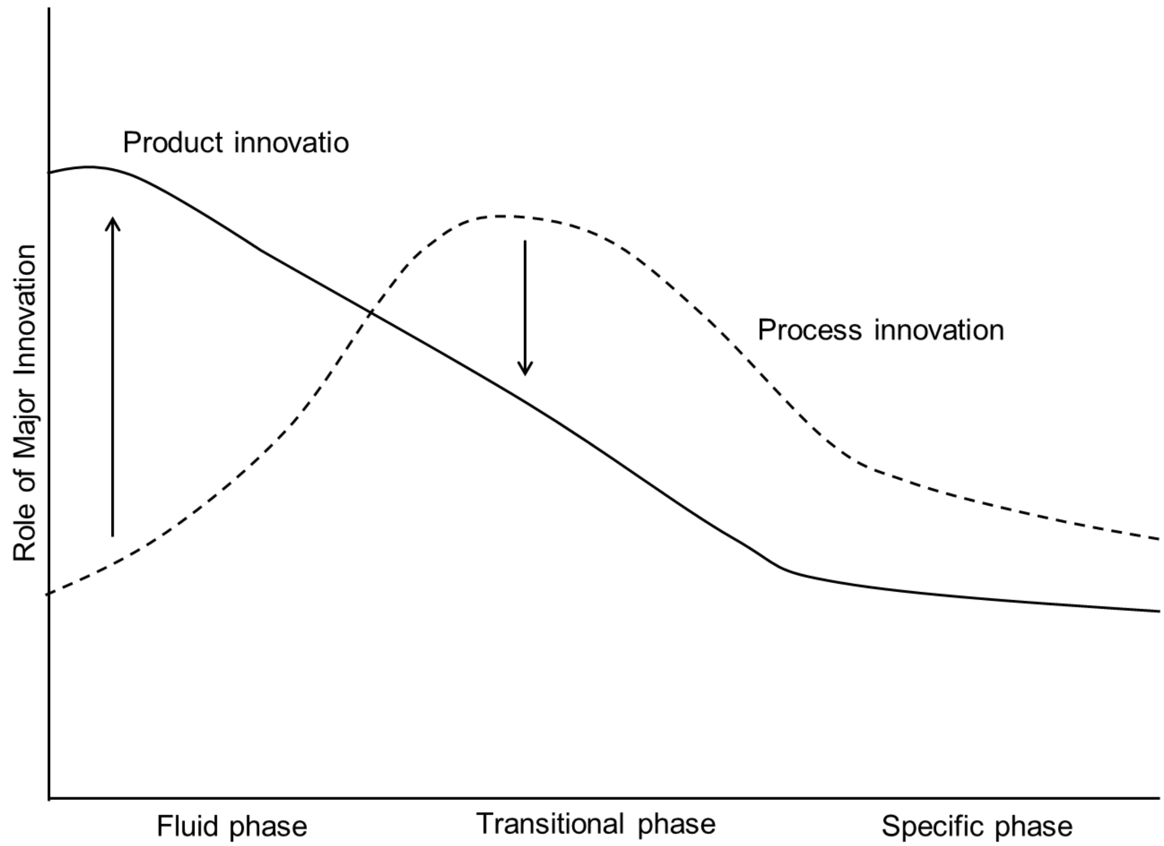

Figure 35 Rapid prototyping's effect on the model of product and process innovation for certain products (c.f. Utterback 1994)

For the suitable products, which can be produced with rapid prototyping technologies, the transitional phase has no meaning. Product innovations turn into prototypes in an efficient manner right from the beginning. This shortens the time needed for the production of prototypes, and as seen, for example, in the case of this research report, this enables shorter design process times. This is possible for two reasons. The first one is the cost structure, where the cost per prototype stays the same, whether one prototype or many prototypes are manufactured. The second reason is that complexity and changes of the design are "free". Changes in the product innovation do not require changes in process innovation and almost any product innovation can be manufactured.

6.2 Move from rapid prototyping to rapid manufacturing can have disruptive effects on many industries and markets

As stated already in the introduction, many believe that 3D printing can fundamentally change the way we manufacture things (e.g. The Economist 2012c, Remes 2012). As Barack Obama stated, 3D printing could be the next revolution in manufacturing (Source: Guardian website <http://www.guardian.co.uk/world/2013/feb/13/state-of-the-union-full-text>). As 3D printing is a highly automated process, cheap labor is not a competitive advantage in the use of it and thus anyone has a possibility to lead this manufacturing revolution.

Additive technologies have the potential to be disruptive in prototyping, but there are still many things to be resolved, before they will be used in a large scale manufacturing of end products. As already mentioned there are limitations in many areas like materials, properties of printed products, accuracy, detail and surface finish. (Hopkinson & Dickens 2003, Hopkinson 2006)

Additive technologies are probably potentially more disruptive in prototyping, because they enable lower costs per product or part in a small series, and only a small series of prototypes are usually needed. Also the limitations of additive technologies do not matter as much in prototypes, because they are not seen by the paying customer with higher quality expectations.

But it can be expected that many of the current limitations of additive technologies are going to be developed as more investments are being made. We might be entering the middle of the S-curve where performance rises fast as investments to the technology rise. (Foster 1986). Thus in the future a wider range of materials could be offered. With FDM and other methods, more different material types could be combined into a single printed product (Erasenthiran & Beal 2006), and the possibility of printed electronics might become available (e.g. The Economist 2012a, Gibson et al. 2010). Development will probably also result as a decline of cost per product produced by rapid manufacturing and larger production volumes will be available (Figure 36).

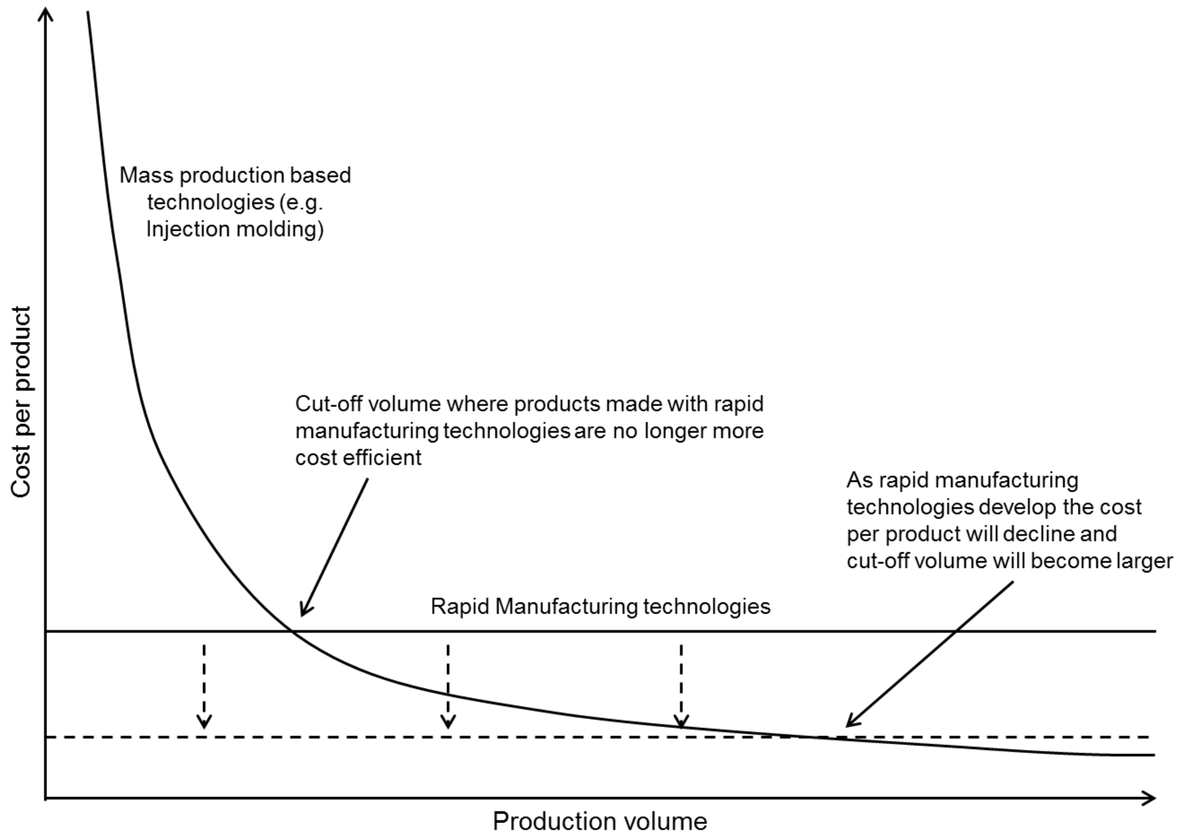

Figure 36 Effect of development of rapid manufacturing technologies to the cut-off volume

One example where 3D printing is used in the production of the end product is Nike Football. Nike Football produces 3D printed plate to its *Nike Vapor Laser Talon* model. The plate of the cleat is crafted using SLS technology. Shane Kohatsu, Director of Nike Footwear Innovation, comments that "SLS technology has revolutionized the way we design cleat plates – even beyond football – and gives Nike the ability to create solutions that were not possible within the constraints of traditional manufacturing processes". (Source: Nike Inc. website <http://nikeinc.com/news/nike-debuts-first-ever-football-cleat-built-using-3d-printing-technology>) This is an example of structure in the end product that cannot be manufactured by any other technology. The plate of the cleat is only one part of the product, but maybe in the future more end products can be manufactured entirely with 3D printing.

Additive technologies could break the interrelationship of product and process innovation also in the manufacturing of end products. The design of a product can be separated from the manufacturing of a product, because all of the needed information necessary to manufacture an object with rapid manufacturing is built into the design. If materials, their combinations, accuracy and surfaces of rapid prototyping technologies develop to match the quality of end products manufactured with other technologies currently in use, the results can be radical. The complexity of a product would not be a limitation with rapid manufacturing technologies, which could produce a wide range of products consisting of different materials, and thus the need for a dominant design would not be that important anymore.

To get the most out of the rapid manufacturing, designers need to be able to unlearn their old restrictions of, for example, DFM and DFA. More imaginative designs can be produced. Rapid manufacturing will also break the divide between mechanical and aesthetic deign. (Hague et al. 2003) Complexity could be close to free and a one of kind product could cost the same as a mass produced product. Variety could also be free as it would cost no more to make every product different than to make them all the same. Production flexibility could be free too. Changing a product after production has started just means changing the instruction code. The rapid manufacturing machines stay the same. The only difference in cost per product, when making one or many, is the difference between dividing the cost of the needed design effort for one or many. Mass customization according to different customers' needs could be possible without losing the efficiency of a process to produce those products.

This can all also pose a threat for current R&D centric companies. As we have already seen with products that changed from physical to digital, like music that moved from CDs to MP3s, illegal copying is a risk. Any part or product can be described in digital CAD form. And almost any digital CAD design could be manufactured with rapid manufacturing, with design complexity as free. Atoms can increasingly start to act like bits.

When this happens, *big-bang disruptions* which are currently based mainly on information technology – the bits, might also start to happen in physical products – the atoms. *Unencumbered development* of designs becomes possible, as no warehouses are needed when products can be manufactured with additive technologies when ordered. Designs can also be tested easily in the markets. Market places for the designs, such as Shapeways, are ready in the Internet. Freedom of Creation (FOC) is an example of a company using this kind of business model already (Source: Freedom of Creation website <http://www.freedomofcreation.com/>). *Unconstrained growth* might also become possible, as long as there would be enough rapid manufacturing capacity to produce the amount of products demanded. (c.f. Downes & Nunes 2013)

6.3 New-market disruptions of rapid manufacturing

Christensen & Raynor (2003) describe how disruptive technologies can create *new-market disruptions*. These disruptions compete with *"nonconsumption"*, as they enable a whole new population of people to begin owning and using the product. Both rapid prototyping and rapid manufacturing can create many different new-market disruptions. The maker movement was already discussed as an example of a new-market disruption of rapid prototyping. Here few examples of possible new-market disruptions of rapid manufacturing are discussed.

Long tail of things

> *"The Internet democratized publishing, broadcasting, and communications, and the consequence was massive increase in the range of both participation and participants in everything digital – the Long Tail of bits. Now the same is happening to manufacturing – The Long Tail of things."* (Anderson 2012, 63)

Designs can already be sold over the ready-made market places. Designs are uploaded to the sites like Shapeways, where the price is given for a design. Anyone can then buy it from there and products will be manufactured using additive technologies. Shapeways takes part of the price for itself and gives the rest for the designer. (Source: Shapeways website <http://www.shapeways.com>) These kinds of market places combined with rapid manufacturing technologies open the supply chains of larger companies to all. The market place, manufacturing and supply chain are already there, if one has a design that has demand for it. There is no need to sell hundreds of thousands of products to make a profit, because cost per product is low also with small series or just one. A few hundred sold products might be enough to cover the costs of design. This has opened the niche markets for physical products – The Long Tail of things.

There is potential for many more new-market disruptions

Rapid prototyping and rapid manufacturing have the potential for several new-market disruptions. Already now they have changed the way things are done in many industries. Rapid manufacturing has changed, for example, the supply chains of the aerospace industry, where supplying spare parts is challenging as stock-outs of critical parts disrupt customer operations. With rapid manufacturing spare parts can be made fast and close to the customer in need (Holmström, Partanen, Tuomi & Walter 2010). This kind of use of rapid manufacturing might be beneficial also to the case company Outotec, as also their mining machines have critical spare parts which stock outs can cause expensive disruptions to customer's operations. There are also numerous medical applications like custom made implants (Wimpenny 2001). It has been predicted for example, that in the future additive technologies can be used for example to manufacture low price houses, fast and efficiently (Soar 2006). 3D printing could also enable new products for the people in poor countries, the bottom of the pyramid. For example 3D printing is planned to be used to produce custom-build compositing toilets and rainwater collectors. The material used, could be recycled high-density polyethylene which can be gotten for example from the used milk bottles. (Source: The Economist website <http://www.economist.com/news/science-and-technology/21565577-new-manufacturing-technique-could-help-poor-countries-well-rich-ones>)

As a summary, additive technologies drive potential disruptions in new-markets and low-end markets. This is why rapid prototyping and rapid manufacturing seem to be hybrid disruptors, combining new-market and low end approaches. (c.f. Christensen & Raynor 2003, 47).

6.4 3D Printing seems to be in the first phase of disruptive technology

I described three phases of disruptive technology in the summary of technology driven business disruptions. According to my evaluation, 3D printing as a technology seems to be currently in the first phase of disruptive technology. (Figure 37)

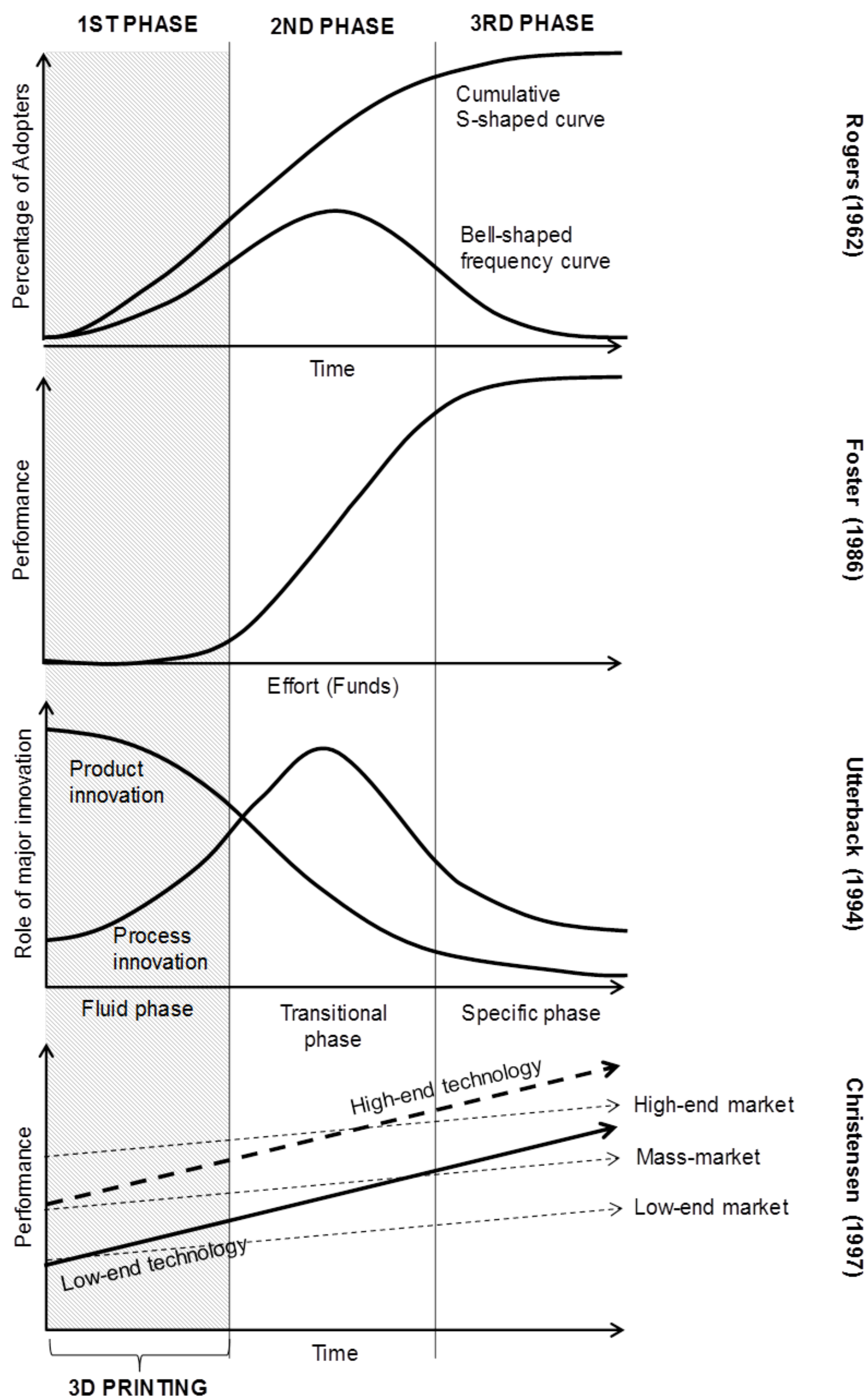

Figure 37 3D Printing seems to be in the first phase of disruptive technology

Most of the current users of 3D printing seem to be innovators and early adopters. They are excited about the new technology and do not need well-established references before investing substantially to the technology (c.f. Moore 1991). According to some evaluations, less than hundred thousand consumer 3D printers (which typically sell for about $1,000 to

$2,000) have been sold. (Source: Wohlers Associates website <http://wohlersassociates.com/p3dp.html>). But the whole 3D printing industry's compound annual growth rate has been in its 24-year history 26.4 percent. By 2015, the sale of 3D printing products and services is believed to reach 3.7 billion dollars worldwide. (Source: Prototype Today web site: <http://www.prototypetoday.com/wohlers-associates/wohlers-associates-publishes-2012-report-on-additive-manufacturing-and-3d-printing>)

Thus it seems that the efforts put into improving 3D printing are rising fast, which can also be seen by the growing investments made to the technology. 3D printing performance is still quite low in those performance metrics that customers value, when compared to other manufacturing technologies. But the performance can be expected to get better as more investments to the technology are made. This is why 3D printing seems to be in the beginning of the S-curve that Foster (1986) has described, but 3D printing might be entering accelerating phase of the S-curve.

The focus around 3D printing seems to be in the experimentation around the product design which is usual in the fluid phase of Utterback's (1996) model of product and process innovation. For example, different 3D printing technologies, which all manufacture products or parts layer-by-layer using different methods, have been developed. Four of them (SLA, SLS, FDM, 3DP) were shortly described in this research report, but there are many more. When the dominant design or designs start to win the allegiance of the marketplace, the investments will probably start to move more to the process innovations, which would mean that more efficient processes to make 3D printers would start to emerge.

As stated before, 3D printing seems to evolve as a hybrid disruptor, which combines new-market and low-end approaches (c.f. Christensen & Raynor 2003, 47). 3D printing offers mostly worse product performance at least in the near term for the manufacturing of parts. Limitations, in for example materials and accuracy, still restricts the possible applications of 3D printing, when compared to the other manufacturing technologies. But 3D printing has brought a different value proposition to the market than had been available previously. Thus 3D printing seems to be currently in the low-end markets. But the rising investments made to the 3D printing technology, might bring more practical and better working full offering solutions for the early adopters and larger already existing mass-markets.

Because 3D printing seems to be in the first phase of disruptive technology, all of the business implications of 3D printing are not seen yet. But more disruptive business impacts might be coming, if the 3D printing industry's compound annual growth rate stays in its current high level. If 3D printing is entering the middle of the S-curve, the explosion, the business implications can start to realize soon. As 3D printing develops as a manufacturing technology, it may also break the tight interrelationship of product and process innovation in the physical products. Then 3D printing could also enable many physical product innovations to move faster through the first phase and make the atoms act increasingly like bits.

6.5 Conclusions

As this research report was conducted based on a qualitative single case study design, there are limitations on the generalization of the results. The theoretical outcome of this research report is suggestive theory building, which primarily offers the basis for further research.

According to this research report, rapid prototyping is a potentially disruptive technology for R&D focused product leadership companies. Rapid prototyping seems to evolve as low-end disruption, where the product performance is first worse than current technologies. But as the rapid prototyping technologies evolve it has the potential to invade existing markets. In the case design process of this research report, rapid prototyping brought many benefits to and replaced the previous technologies used. Rapid prototyping has also enabled new customers to produce prototypes which previously could not afford the technologies needed and thus it can be seen as a new-market disruption too.

It seems that the context where rapid prototyping is used defines also whether rapid prototyping can be seen as a disruptive technology or not. Thus further research is needed to describe different contexts where rapid prototyping, as a disruptive technology, can replace the existing technology as the dominant technology or to bring prototyping to new customers as a new-market disruption.

Rapid prototyping and rapid manufacturing can break the tight interrelationship of product and process innovation which Utterback (1994) has described. If this happens, then product innovations may be brought to markets faster and with efficient processes to produce them right from the beginning close to the consumption. This could have numerous disruptive implications for many business models. As Gartner expects, the 3D printing technology maturity is not yet sufficient even though the hype around it is at its peak (Gartner 2012). But R&D focused product leadership companies should follow the progress of 3D printing closely, because of its disruptive potential.

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APPENDIXES

APPENDIX 1: Structure for interviews

1. How the need to change the design of vacuum connection was recognized?
2. Why rapid prototyping was selected?
3. How and in which different phases the prototyping has progressed?
4. How rapid prototyping has influenced in each of the phases?
5. How design process and prototyping of vacuum connection had been progressed, if rapid prototyping would not have been used?
6. Have there been any problems or surprises?
7. When and why the use of rapid prototyping was decided to be ended (and move to another manufacturing technique)?

APPENIX 2: Operating principles of Outotec Larox CC

1. Cake forming

Cake forming takes place on the discs when they rotate through the slurry. Capillary action creates an extremely high vacuum level, which draws liquid through the discs into the filtrate lines. Solids build up rapidly on the external surfaces of the discs, and the microporous structure prevents any solids from penetrating the disc surface. The driving force is generated by a small 2.2 kW vacuum pump.

2. Cake drying

As the discs rotate, capillary action continues in an uninterrupted manner across the disc surface until all free liquid is removed from the solids. No air penetrates the disc surface. The result is an exceptionally dry cake at a fraction of the energy required by conventional filtration techniques.

Cake washing (optional)

Wash liquid is sprayed evenly and gently on the cake solids. This process removes additional filtrate or impurities and achieves a true displacement wash. High wash efficiency is reached with low liquid consumption. This is a significant benefit when dewatering concentrates produced in plants using saline process water.

3. Cake discharge

Scrapers remove the cake from the discs. A thin residual cake is left on the surface to protect against mechanical abrasion. This reduces maintenance requirements and extends the life of the discs. Continuous cake discharge is achieved without the need for a snap blow.

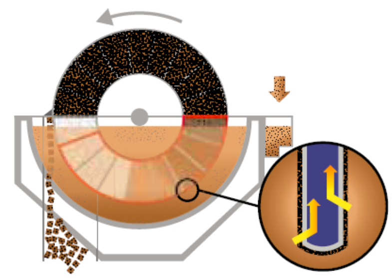
4. Backflow washing

Filtrate is used to flush the discs. It removes residual cake and cleans the microporous structure. Backflow washing helps the discs retain their exceptional filtration efficiency and ensures long, trouble-free life. Backflow washing is automatic and adjustable for each application.

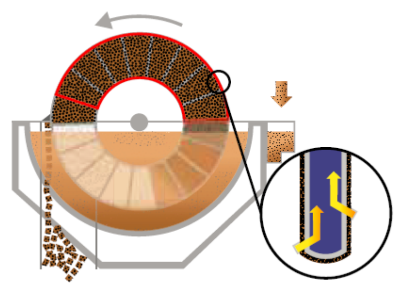
5. Disc regeneration

Instead of discarding the filter media, ceramic plates can be regenerated and full permeability returned. Periodic cleaning is performed automatically with built-in chemical and ultrasonic systems.

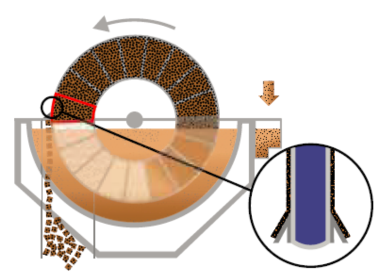
Slurry
Filtrate
Wash liquid
Solids



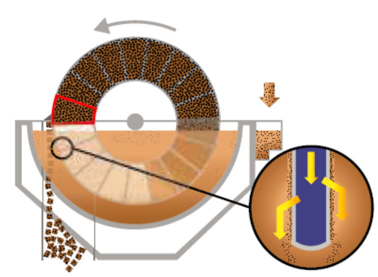
1. Cake forming



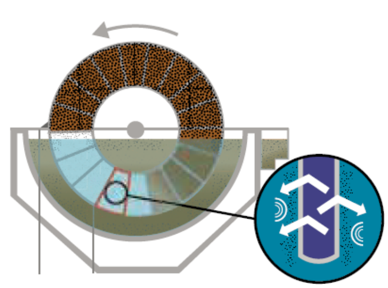
2. Cake drying



3. Cake discharge



4. Backflow washing



5. Disc regeneration

APPENDIX 3: Summary of the case